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A Study of the Dielectric Strength of Air

Electrical Engineering

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A STUDY OF
THE DIELECTRIC STRENGTH OF AIR

BY

LEO MAHLON APGAR

B. S. University of Illinois, 1912

THESIS

Submitted in Partial Fulfillment of the Requirements for the

Degree of

MASTER OF SCIENCE

IN ELECTRICAL ENGINEERING

IN

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

Leo Mahlon Apgar

ENTITLED A Study of the Dielectric Strength of Air.

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF Master of Science in Electrical Engineering

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I. INTRODUCTION.

It is well known that an electric field exists around a charged body placed in a dielectric and it is known that the strength of the field and its distribution depends upon the charge and shape of the charged body. It is believed that if no ions are present, the field might be uniform between the coatings of a condenser consisting of two parallel plates and that its intensity varies inversely as the square of the radius when the charge is given to a sphere isolated in space. It is suspected that the dielectric is only able to sustain a certain intensity of electric field; so that when the field becomes too dense, that is when the potential gradient is too great, the dielectric breaks down. Based upon a number of experiments at which however direct current at rather low voltage was used it was concluded by scientists years ago that the maximum gradient that air could sustain was 30,000 volts per cm.

It is the principal purpose of this thesis to determine the maximum value of the potential gradient of air by means of alternating currents at high voltages. The major work was done by subjecting two equal spheres separated by various distances to high potential differences. A small amount of work - largely for checking purposes - was done with needles instead of spheres. The point of breakdown was assumed to correspond to that particular voltage at which corona first appeared.

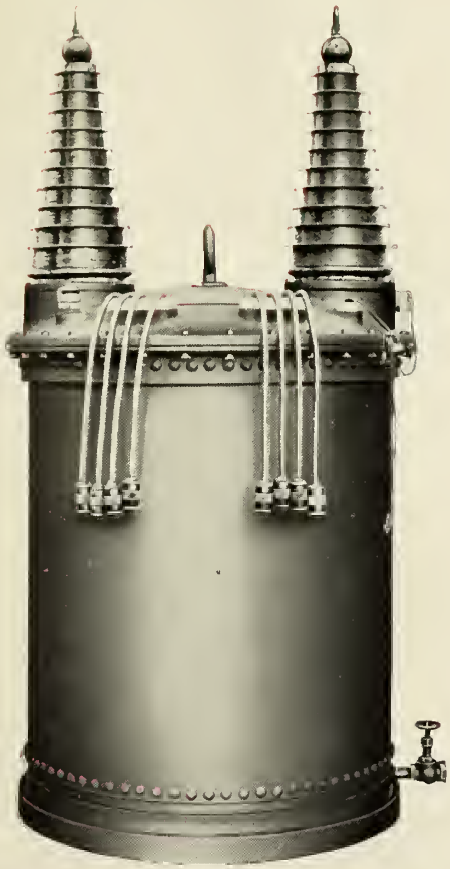
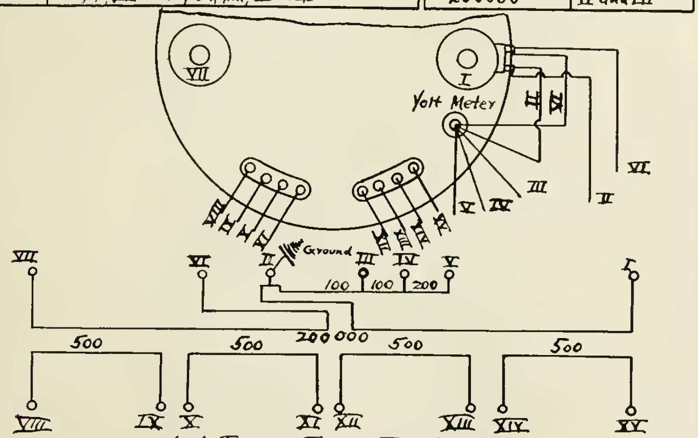


FIGURE I
A 200,000 VOLT TRANSFORMER
Courtesy The General Electric Co.

Low Tension Connections	
Lines on VIII and XV	
Volts	Connect
2000	IX to X, XI to XII, XIII to XIV
1000	VIII to XII, IX to X, XI to XV, XII to XIV
500	VIII, X, XII and XIV, XV, XIII, XI and IX

Volt Meter Connections	
Volts	Lines on
50000	II and V
100000	II and IV
200000	II and III



High Tension Testing Transformer
Start (I) of Winding is at bottom
Low Tension Winding Consists of 4 Coils 500 Volts each
Voltmeter Coil - 100-200-400 Volts.
Start of voltmeter Coil is Connected to middle point of High Tension Winding and is grounded to core
When using Wattmeter between VI and II film cut out should be held open by a sheet of Cigarette paper.

FIGURE 2

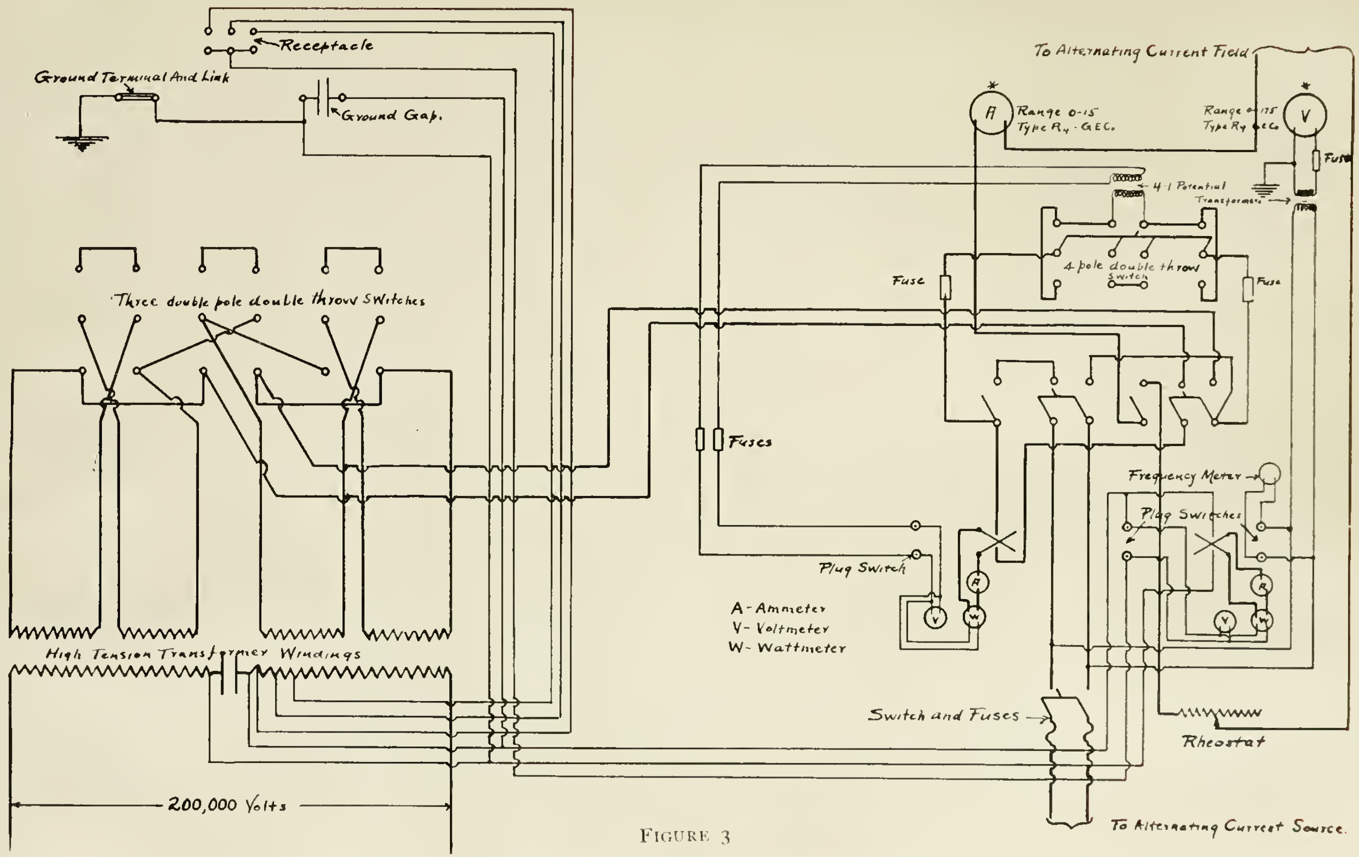


FIGURE 3

SWITCHBOARD WIRING (Back View)

All Meters Not Marked With * Are Enclosed in Drawers

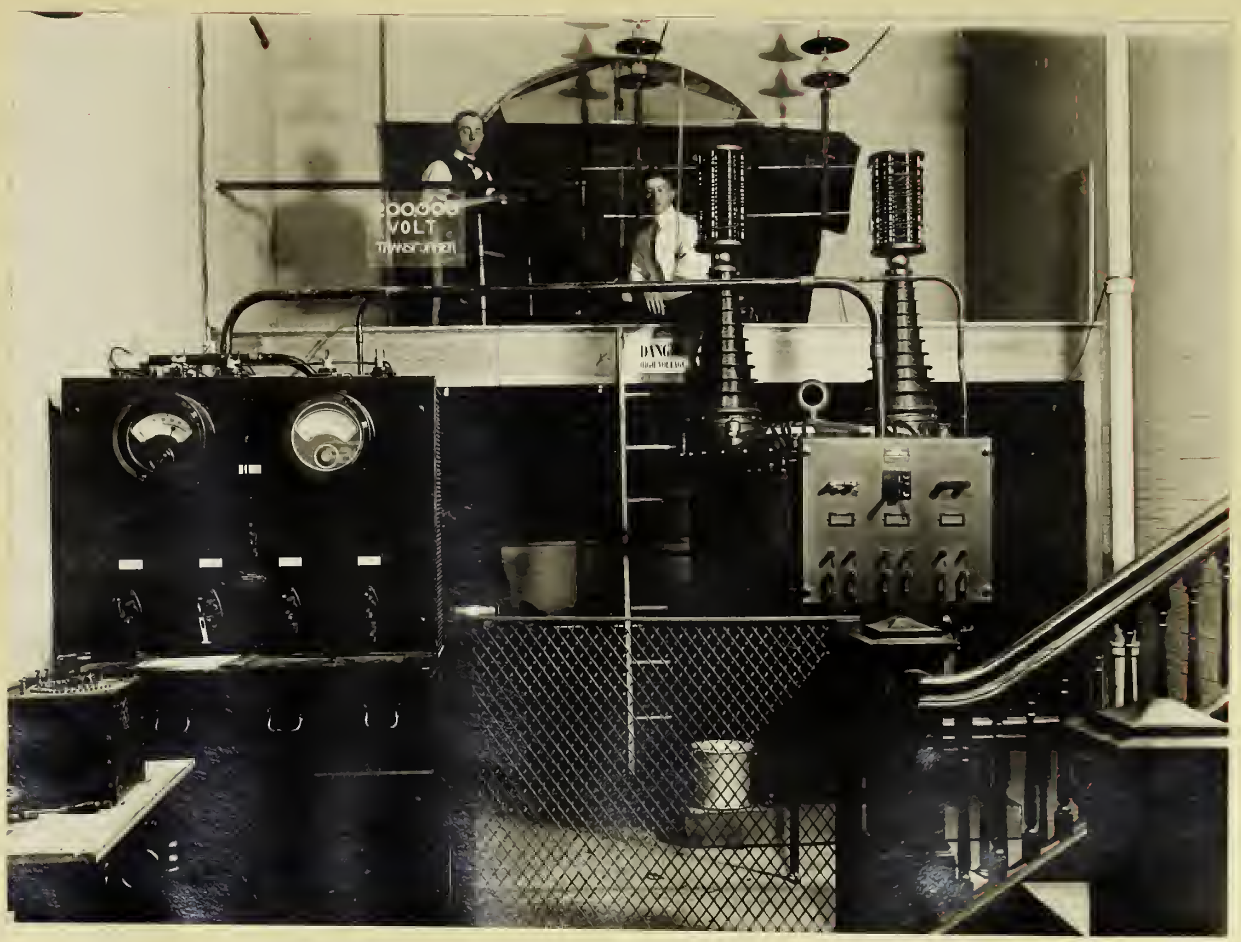


FIGURE 4
General Layout Of Apparatus

II. DESCRIPTION OF APPARATUS.

The high voltages used were obtained from a special testing transformer (Fig. 1.) manufactured by the General Electric Company which was of the following rating.

Capacity:- 100 K.W. at 60 cycles.

Voltage Ratio:- 500-1000-2000 to 200,000.

Current Ratio:- 50-0.5.

Ratio of windings as used:- 400 to 1.

For all tests the neutral of the transformer was grounded.

As shown in Fig. 4 two switchboards were provided. The one to the right, near the transformer, contains the low tension coil grouping switches and high tension instrument taps which are shown in the left of Fig. 3.

On the switchboard to the left in Fig. 4 are mounted the control switches and meters. All meters in the transformer circuits are in drawers which are covered with plate glass. These drawers are so constructed that all connections are broken when drawers are opened. The circuits on this board are shown on right of Fig. 3.

To limit the flow of current between the spark gap terminals on breakdown of the gap, non-inductive resistance was inserted. As it was desired to limit the current to one tenth amperes at 200,000 volts pressure 2,000,000 ohms of resistance were needed. Carborundum rods were experimented with but these gave varying resistances and had a negative resistance coefficient; therefore two glass tubes, filled with distilled water to which dilute sulphuric acid was added, were used and they could easily be adjusted to 1,000,000 ohms per tube.

To prevent travelling waves in the transformer windings, two choke coils of 40 turns of #14 wire each, wound on spools of dimens-

ion 8inches by 16 inches, were placed in series with the gap.

The spark gap apparatus (Fig. 5.) was suspended from two heavy copper rods held by strings of four suspension insulators and consisted of two vertical wooden strips clamped to two horizontal glass

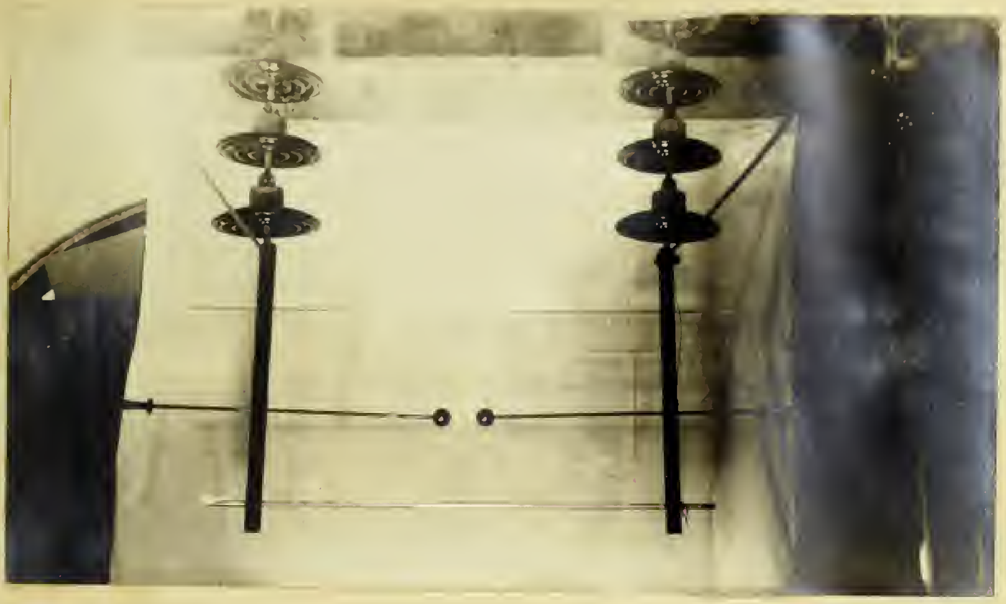


FIGURE 5.

rods. Midway between the glass rods on the wooden strips were two brass bearings which were connected to the transformer. In these bearings rested brass rods which had their ends threaded; so that the spheres could be attached. By sliding the rods in or out the various gap lengths could be obtained and measured by means of calipers.

Three different electric generators were used; so that the effect of the wave shape might be studied. The wave shapes are given in Fig. 6.

The rating of above mentioned machines are as follows:

45 K.W. WESTINGHOUSE SET:- 45 K.W., 2 phase, 440 volt generator belted to 45 K.W. 220 volt D.C. motor.

85 K.W. WESTINGHOUSE SET:- Direct connected 2 phase 440 volt generator and 220 volt D.C. motor.

SMOOTH CORE MACHINE:- Thomson Houston Electric Co., 1100 volts

III. GENERAL THEORY.

The potential gradient may be defined as the rate of change of voltage with the distance, or if

f, represents the potential gradient

V, the electromotive force or effective e.m.f.

x, the distance between any two terminals.

Then $f = -\frac{dV}{dx}$

To derive a formula for the maximum potential gradient of air between any two spheres at any distance the theory of electrostatics will be used. To be accurate the system of successive images as given in Maxwell should be used but this would result in a formula too complicated to be of practical use; so the approximate method given below is used and will answer for all practical purposes.

Let A and B in Fig. A represent two equal spheres at any distance charged respectively with a charge +Q and -Q. Assume charges to be point charges at O and O' respectively.

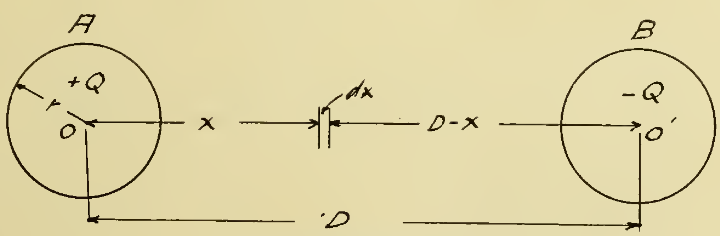


FIGURE A.

The flux $\Phi = 4\pi Q$

Since $\Phi = 4\pi \Sigma q$ where q = capacity charges.

Let R be the electric field intensity.

Then $R = \frac{\Phi}{\text{area}} = \frac{4\pi Q}{4\pi r^2} = \frac{Q}{r^2}$

At any distance x from a charge Q

$$R = \frac{Q}{x^2}$$

In the following theory, primed letters refer to sphere A and double primed ones to B.

Then $\quad R' = \frac{Q}{x^2}$ where R' is due to charge on A, and x is distance shown in Fig. A.

$$V = -\int R'dx \quad \text{for air}$$

$$= -\int \frac{Q}{x^2} dx = \frac{Q}{x}$$

$$f' = -\frac{dV}{dx} = \frac{Q}{x^2} = R'$$

Similarily $\quad R'' = -\frac{Q}{(D-x)^2} = f''$

And $\quad f = f' + f''$ (numerically)

$$= Q\left[\frac{1}{x} - \frac{1}{(D-x)^2}\right] = -\frac{dV}{dx}$$

Therefore $\quad V = Q\left[\frac{1}{x} - \frac{1}{(D-x)}\right]_r^{D-r} = Q\left[\frac{1}{D-r} - \frac{1}{r} - \frac{1}{r} + \frac{1}{D-r}\right]$

$$= 2Q\left[\frac{1}{(D-r)} - \frac{1}{r}\right]$$

Therefore $\quad Q = \dfrac{V}{2\left(\frac{1}{D-r} - \frac{1}{r}\right)}$

Substituting value of Q in equation for f

$$f = \frac{V}{2\left(\frac{1}{D-r} - \frac{1}{r}\right)}\left[\frac{1}{x} + \frac{1}{(D-x)^2}\right]$$

f is maximum at the surface of the spheres when the corona ball is of the same diameter as the spheres themselves or $x = r$

Therefore $\quad f = \left[\frac{V}{2}\,\frac{(D-r)^2 - r^2}{r(2r-D)(D-r)}\right]$

But $\quad 2r-D = -X$

Therefore $\quad f = -\frac{V}{2X}\left[\frac{(D-r)^2 - r^2}{r(D-r)}\right]$

Since X in this formula is the distance between the fictious corona balls it becomes necessary to find their diameters. Just before corona appears it is evident that the corona ball and sphere

must be of the same diameter since immediately after corona is visible the corona ball is the larger; therefore one is now confronted with the proposition of finding the length of gap at which corona first appears.

As this distance is very difficult to observe, especially if it is not known within two or three centimeters, a graphical method of finding it is developed below.

Up to a certain length of gap between the spheres only breakdown occurs. After this point (which will be called the critical point) is reached corona will first appear and then if the voltage is increased breakdown will occur at a higher value, depending upon the length of gap.

It was found experimentally that the corona voltage followed a smooth curve which was somewhat similar to a parabola while the breakdown voltage varied in a straight line for several thousand volts after the critical point had been passed. If the breakdown line (the straight line) is produced to intersect the corona line, the point of intersection will give the distance and voltage at which corona first appears, and this distance and voltage is the one used in calculating the maximum potential gradient.

Geo. R. Dean of the University of Missouri has deduced a formula for the potential gradient, using point charges. By means of trigonometry he has expressed the gradient as

$$f = \frac{V}{4X}\left[\frac{X}{\rho} + 1 + \sqrt{\left(\frac{X}{\rho} + 1\right)^2 + 8}\right]$$

where X is length of spark gap,

and ρ is radius of curvature,

V is effective potential difference.

The maximum difference between the values of the gradient computed

by this formula and those computed by Russell's is about one-half of one percent and occurs in the neighborhood of $\frac{X}{a} = 1.5$, X being spark gap and a the radius.

Table #10 shows the potential gradients as calculated by the three different methods and the percent difference between them.

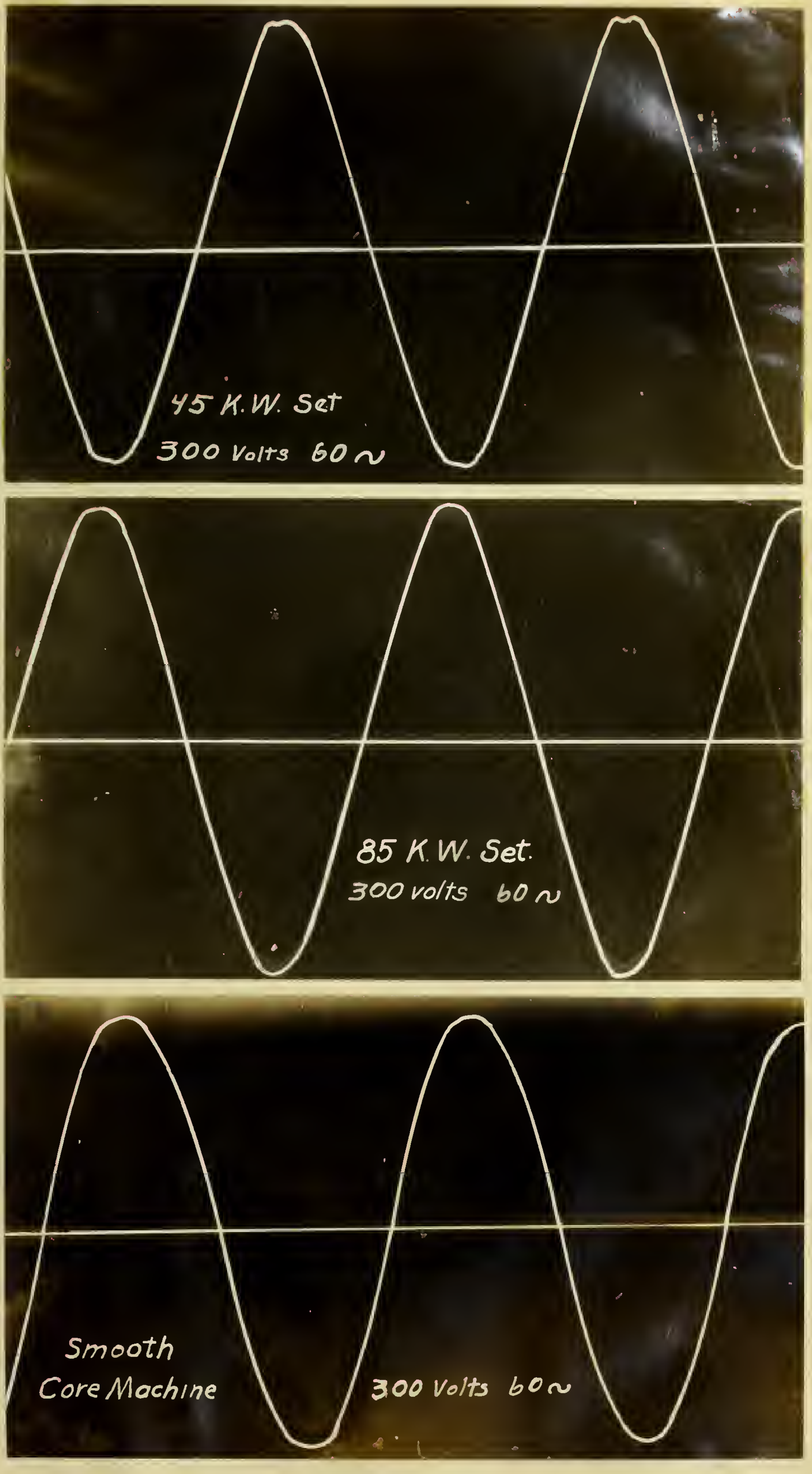

45 K.W. Set
300 Volts 60 ~
85 K.W. Set.
300 volts 60 ~
Smooth
Core Machine
300 Volts 60 ~

FIGURE 6

IV. DATA AND DISCUSSION OF RESULTS.

Article 1.

Needle Gaps.

All the results tabulated are the average of two or more readings for each length of gap (X) during a test.

Along with the study of potential gradient and corona the needle gap was investigated. Sharp's No. 1. needles were used throughout the tests. In Plate I. the points obtained by using the 45 K.W. set were plotted along with Peek's and the A.I.E.E. curves. Peek has straight lines which intersect at 35,000 volts and 5 cm. distance, the A.I.E.E. gives a curved line starting at zero, while the data obtained in the tests, using the 45 K.W. set, gives a line with a reverse curve in it. Thinking that perhaps the wave shape of this set was such that resonance was obtained which would affect the results, two other machines, an 85 K.W. set and a smooth core generator, were also used and data obtained. This data is given in table #1 and plotted in Plate II.

The wave shapes of each of the machines can be seen by referring to Fig. 6. which gives the oscilliograms taken from each.

Referring to Plate III. it will be seen that the smooth core machine which has practically a sine wave, gives a curve that comes nearer coinciding to that of the A.I.E.E. but even at the best does not follow it closely. The 85 K.W. & 45 K.W. sets have nearly the same wave shape as can be seen by referring to Fig. 6. and the curves for the needle gaps are practically the same, the ordinates of the 85 K.W. one being a trifle higher.

Dr. C. P. Steinmetz states that the breakdown of the air is due to the maximum value of e.m.f. Referring again to Fig. 6. it

will be noted that even though all the effective values of e.m.f. are the same, the maximum value of the smooth core machine is the smallest, and then referring to Plate 2. it will be observed that for the same gap a higher effective e.m.f. is required for breakdown with the smooth core machine which means that the maximum had to be increased to that of the other machines.

In table #2 the results of an investigation of the effect of size and shape of terminals on the breakdown voltage of the needle gap are tabulated. It was found that placing of conducting materials such as balls of tinfoil back of the needle points made no difference in the breakdown voltage but that the length of needle protruding beyond holder increased the voltage necessary for breakdown.

TABLE #1.

FOR NEEDLE POINTS.

Temp. 27 C. Rel. Humidity 56-53%

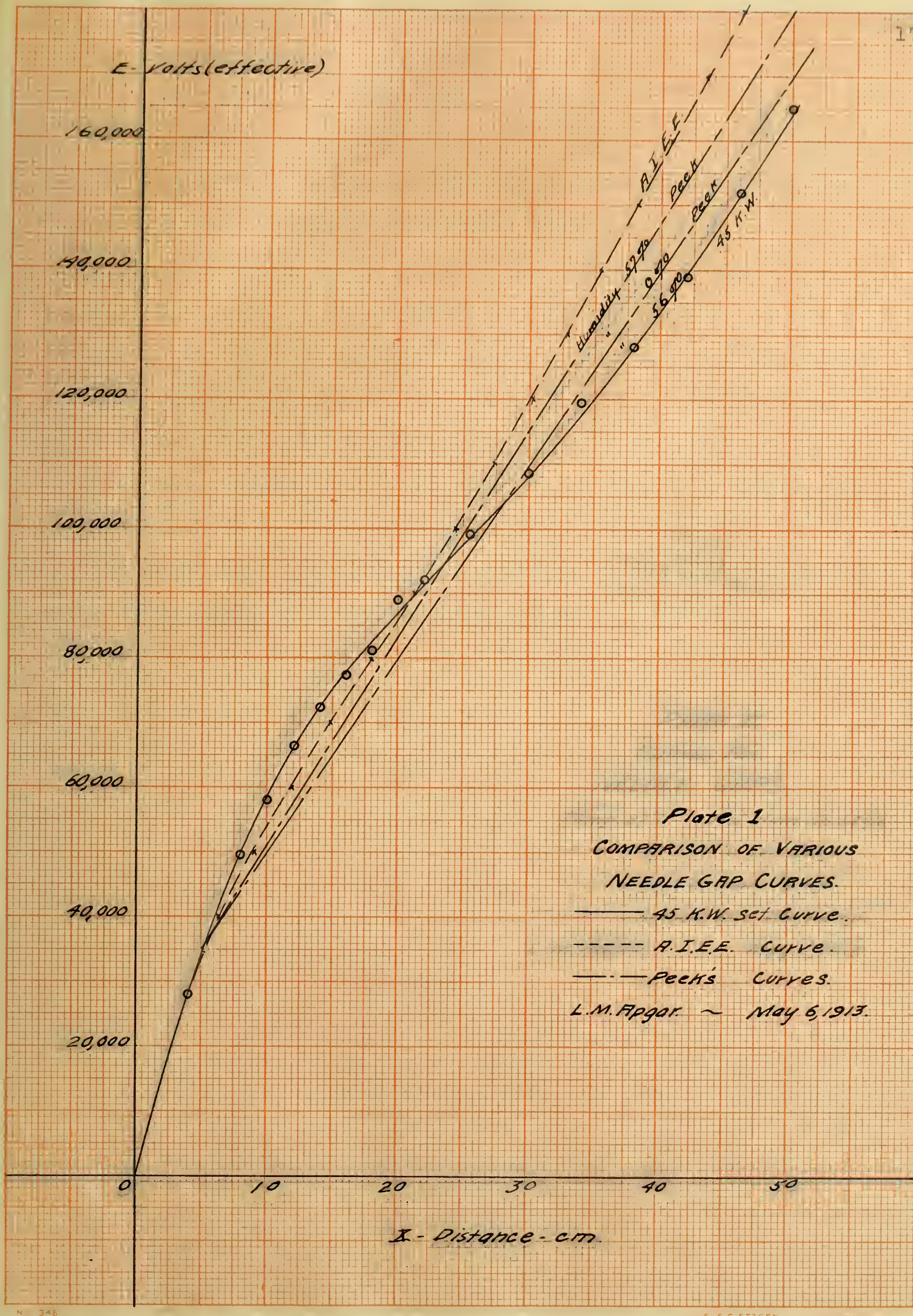
X cm.	BREAKDOWN VOLTAGES Smooth Core KV.	85 K.W. KV.	45 K.W. KV.	NOTES
4	30.5	30.0	28.0	Sharps #1 Needles Used
8	53.5	51.5	49.5	
10			58.0	
12	71.3	69.0	66.5	
14			72.5	
16	80.5	78.0	77.5	
18			81.0	86.0 after breaking
20	88.5	89.0	89.0	
22			92.0	95.0 after breaking
24	97.5	98.0		
26			99.0	109.0 " "
28	109.0	109.0		
30			108.5	130.0 " "
32	120.0	112.0		
34			119.5	
36	131.0	124.0		
38			128.0	
40	140.5	135.0		
42			139.0	
44	152.0	146.0		
46			152.0	
48	164.0	161.0		
50			165.0	

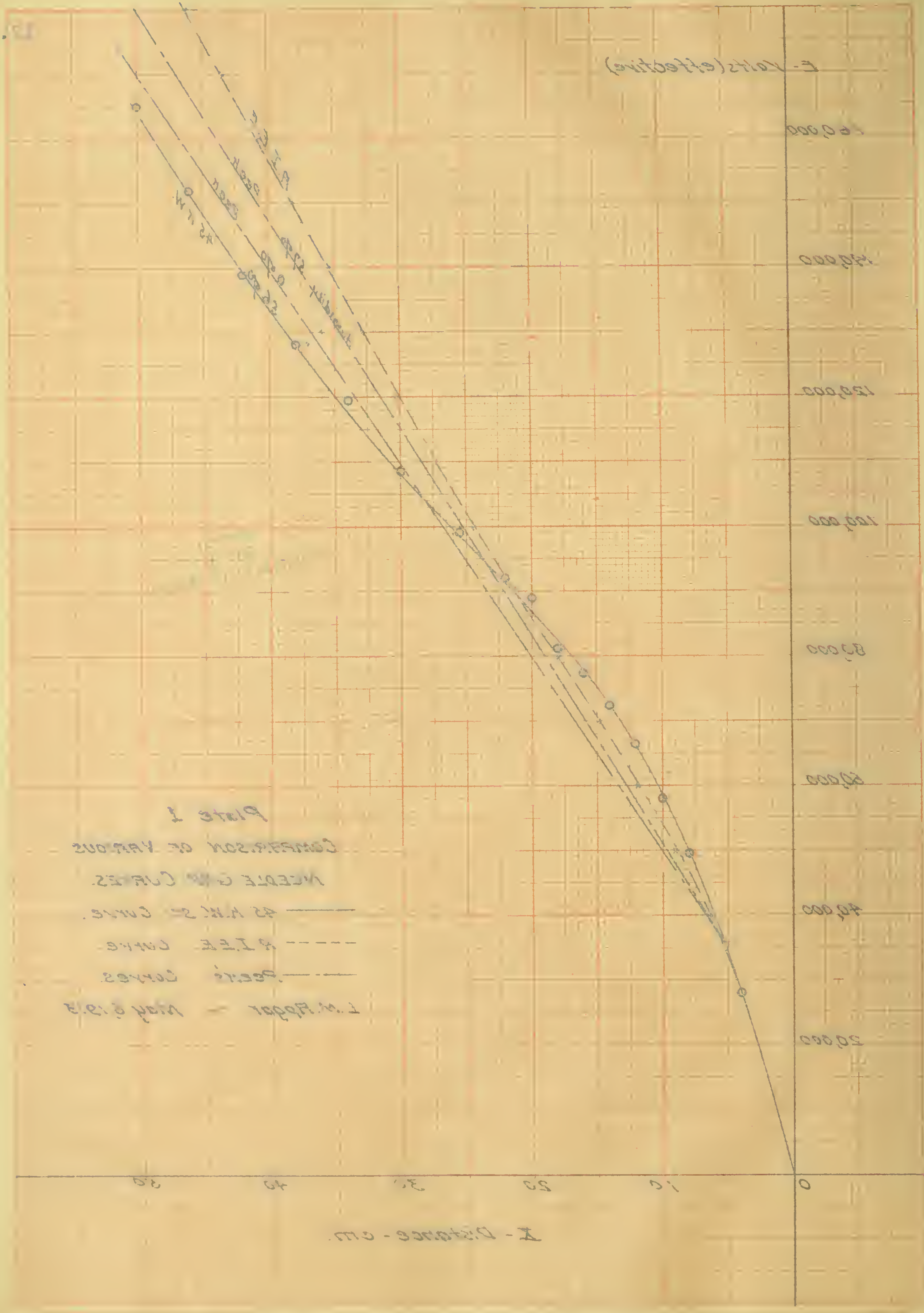
TABLE #2

EFFECT OF TERMINALS ON NEEDLE GAP.

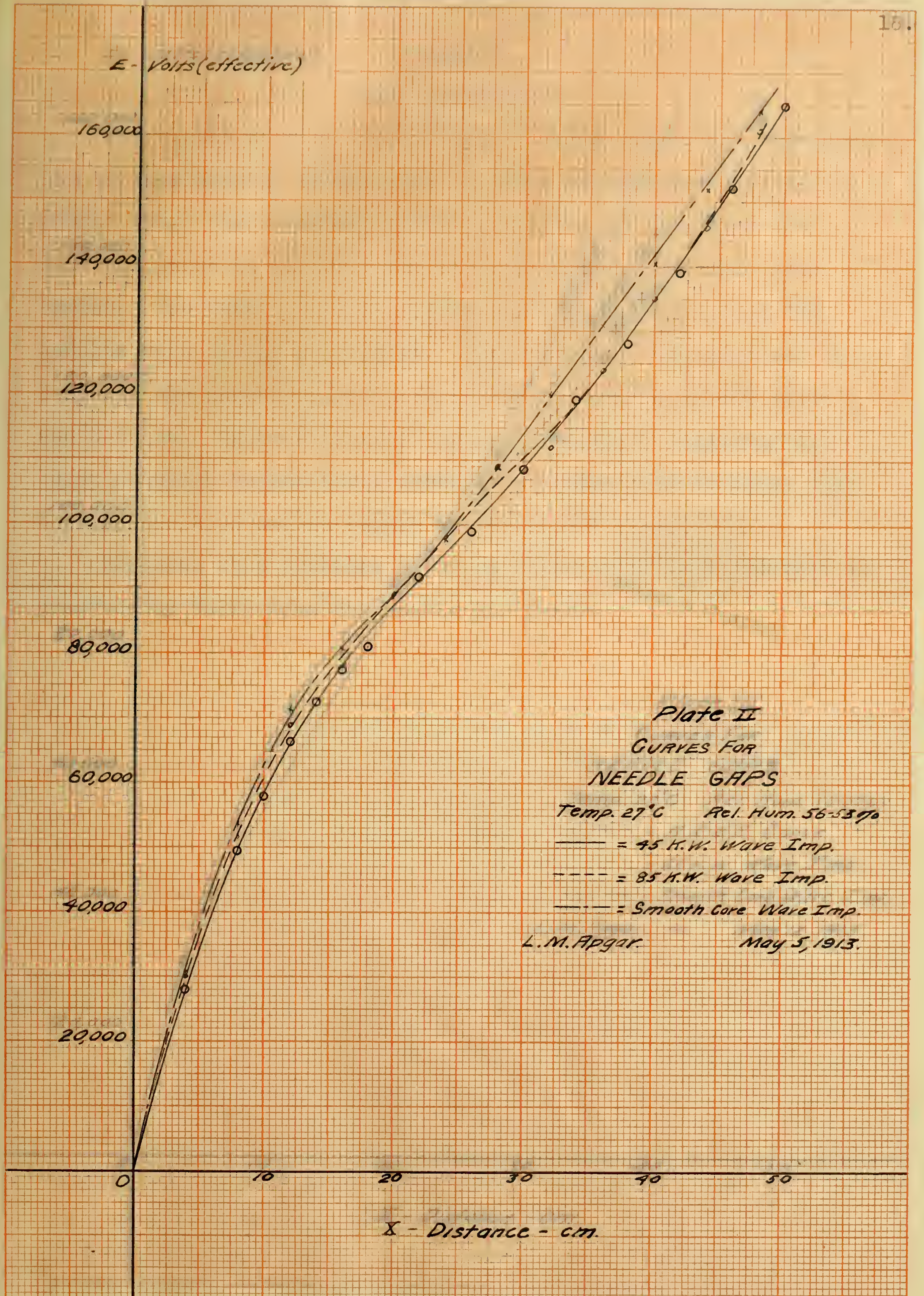
Temp. 27 C Relative Humidity 56-53 %

X cm.	Breakdown KV.	Notes.
10	58	3 cm. of needle protruding.
	56	1 cm. " " "
	59	blast of air on 3 cm. of needle.
	58	point just beyond tinfoil ball.
50	165	3 cm. needle protruding.
	165	4 cm. " "
	164	1 cm. " "
	165	blast of air on 3 cm.
	165	tin foil around rod.
	170	point just beyond tinfoil ball.
	165	2 ft. disks on rods.


E - Volts (effective)
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
10
20
30
40
50
X - Distance - cm.
A.I.E.E.
Humidity 57%
Peek
" 0%
Peek
" 56%
45 K.W.
Plate 1
COMPARISON OF VARIOUS
NEEDLE GAP CURVES.
45 K.W. set Curve.
A.I.E.E. Curve.
Peek's Curves.
L.M. Apgar. ~ May 6, 1913.



E - Volts (effective)
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
10
20
30
40
50
X - Distance - cm.
Plate I
Comparison of Various
Needle Gap Curves.
A.I.E.E. Curve.
Peek's Curves.



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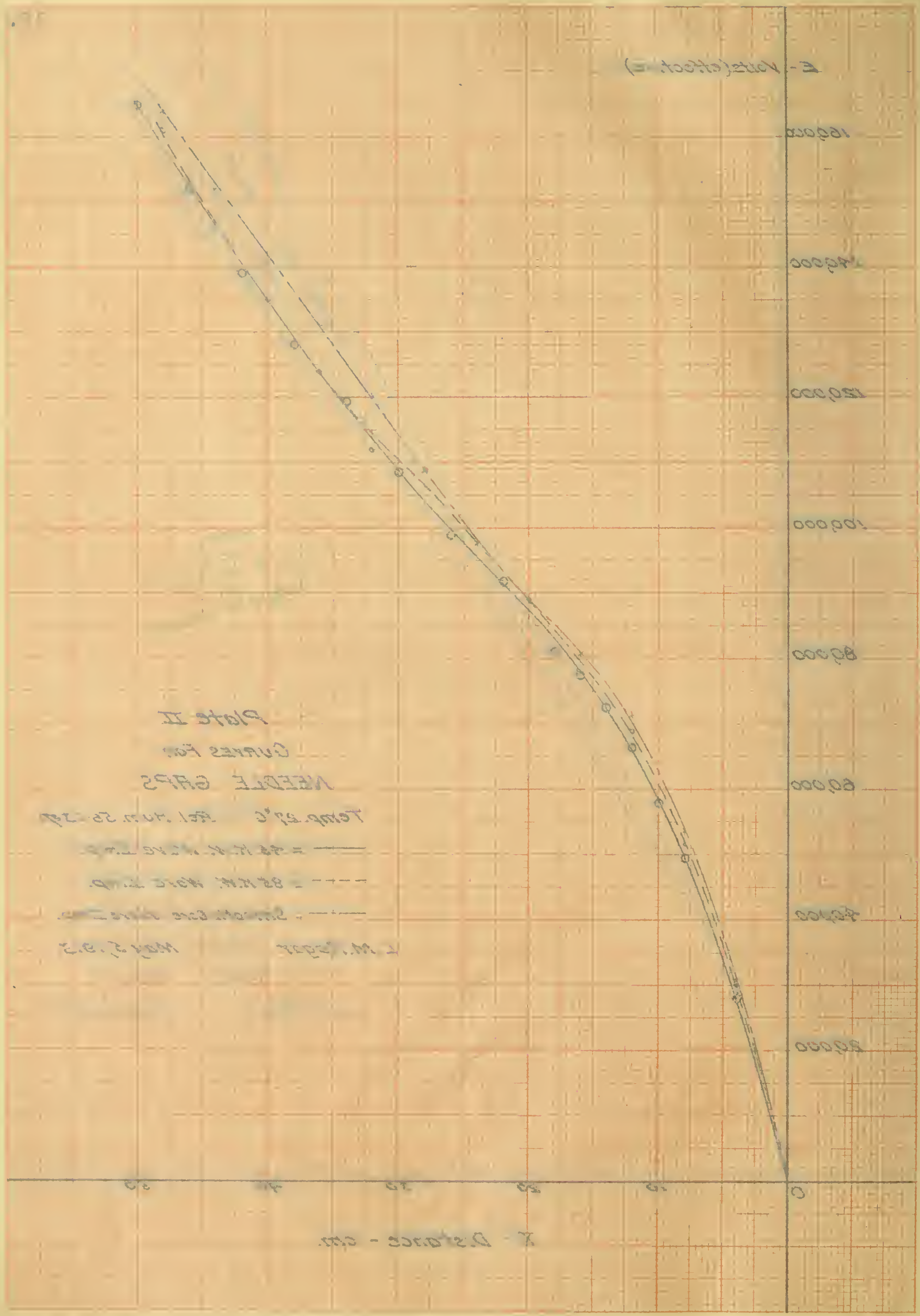
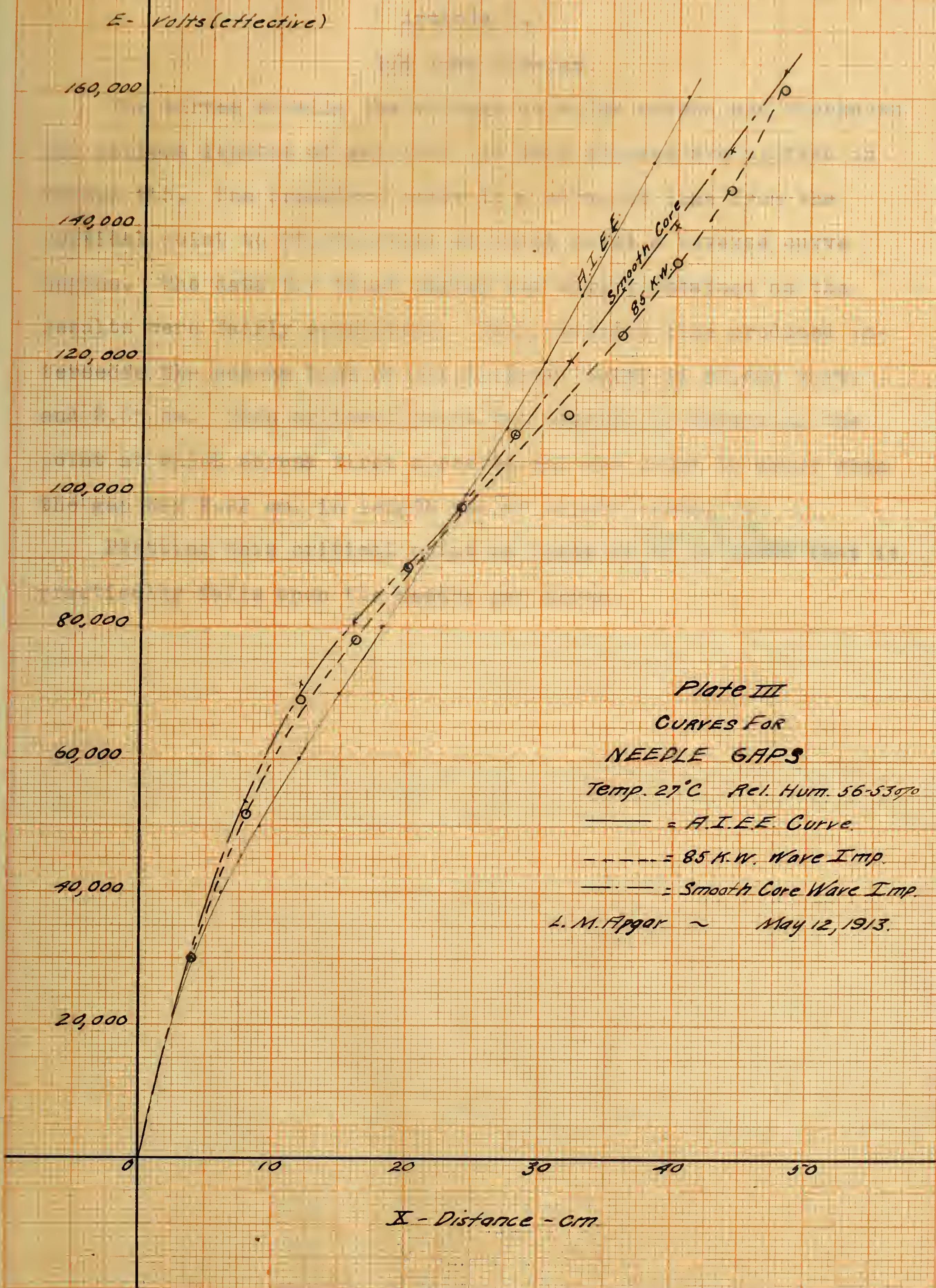
EUGENE DIETZGEN CO. CHICAGO-NEW YORK


E - Volts (effect.)
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
Plate II
Curves for
NEEDLE GAPS
X - Distance - cm.


E- Volts (effective)
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
10
20
30
40
50
X - Distance - cm
A.I.E.E.
Smooth Core
85 K.W.
Plate III
CURVES FOR
NEEDLE GAPS
Temp. 27°C Rel. Hum. 56-53%
= A.I.E.E. Curve.
= 85 K.W. Wave Imp.
= Smooth Core Wave Imp.
L. M. Apgar ~ May 12, 1913.

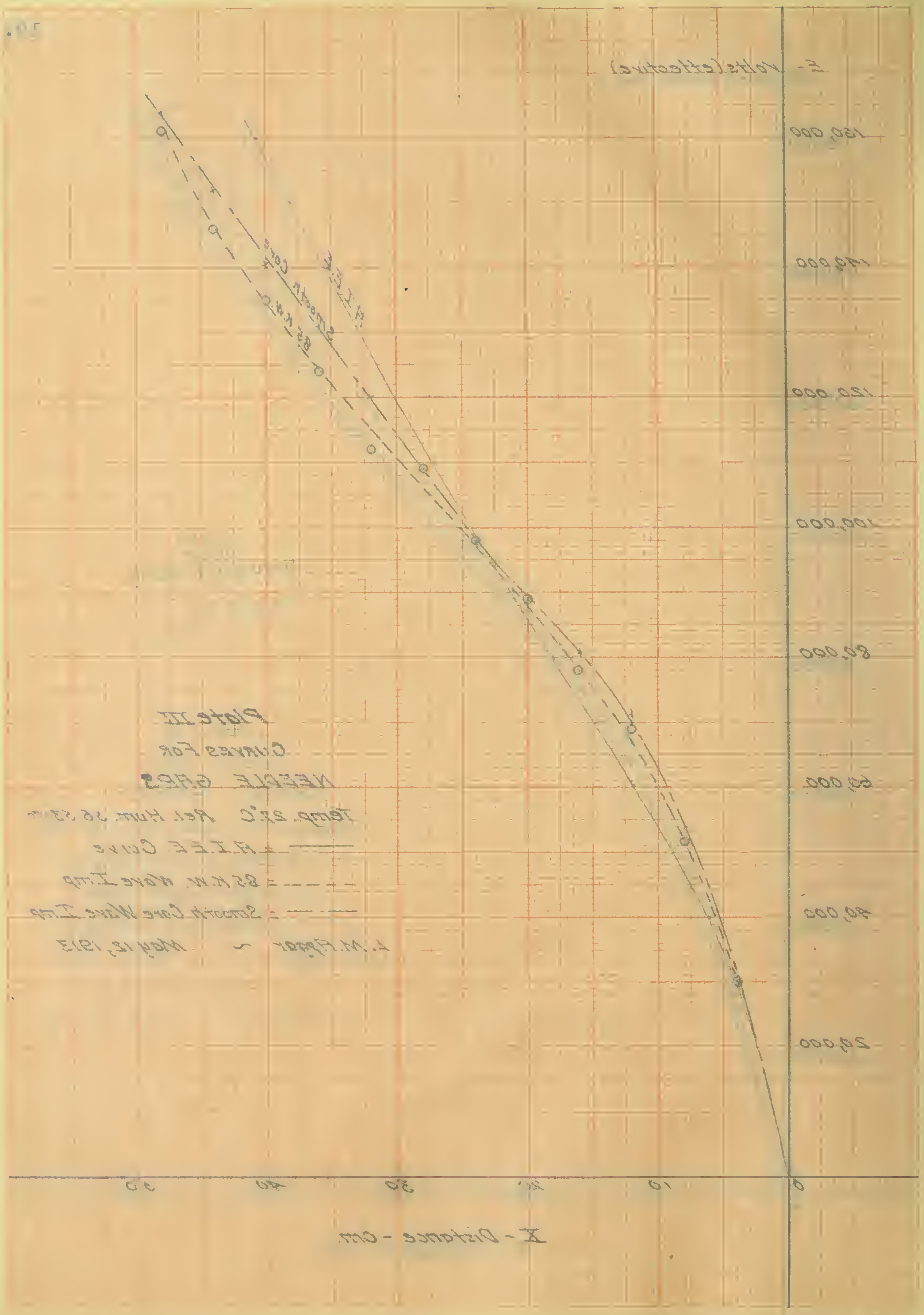


Plate III
Curves for
NEEDLE GAPS
Temp. 22°C Rel. Hum.
A.I.E.E. Curve
85 K.W. Wave Imp
Smooth Core Wire Imp
May 12, 1913
E - Volts (effective)
150,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
10
20
30
40
50
X - Distance - cm.

Article 2.

1/4 Inch Spheres.

The curves showing the voltage at which corona and breakdown for various lengths of gap with 1/4 inch spheres are plotted in Plates 4&5. The breakdown curve is a straight line from the critical point to 98,000 volts at which point a reverse curve begins. The data for these curves was easily obtained as the results were fairly consistent. This straight line produced intersects the corona line at the critical point of 22,600 volts and 2.65 cm. This critical point was checked by observing the point at which corona first appeared and was found to occur when the gap was 2.65 cm. in length and at 22,600 volts.

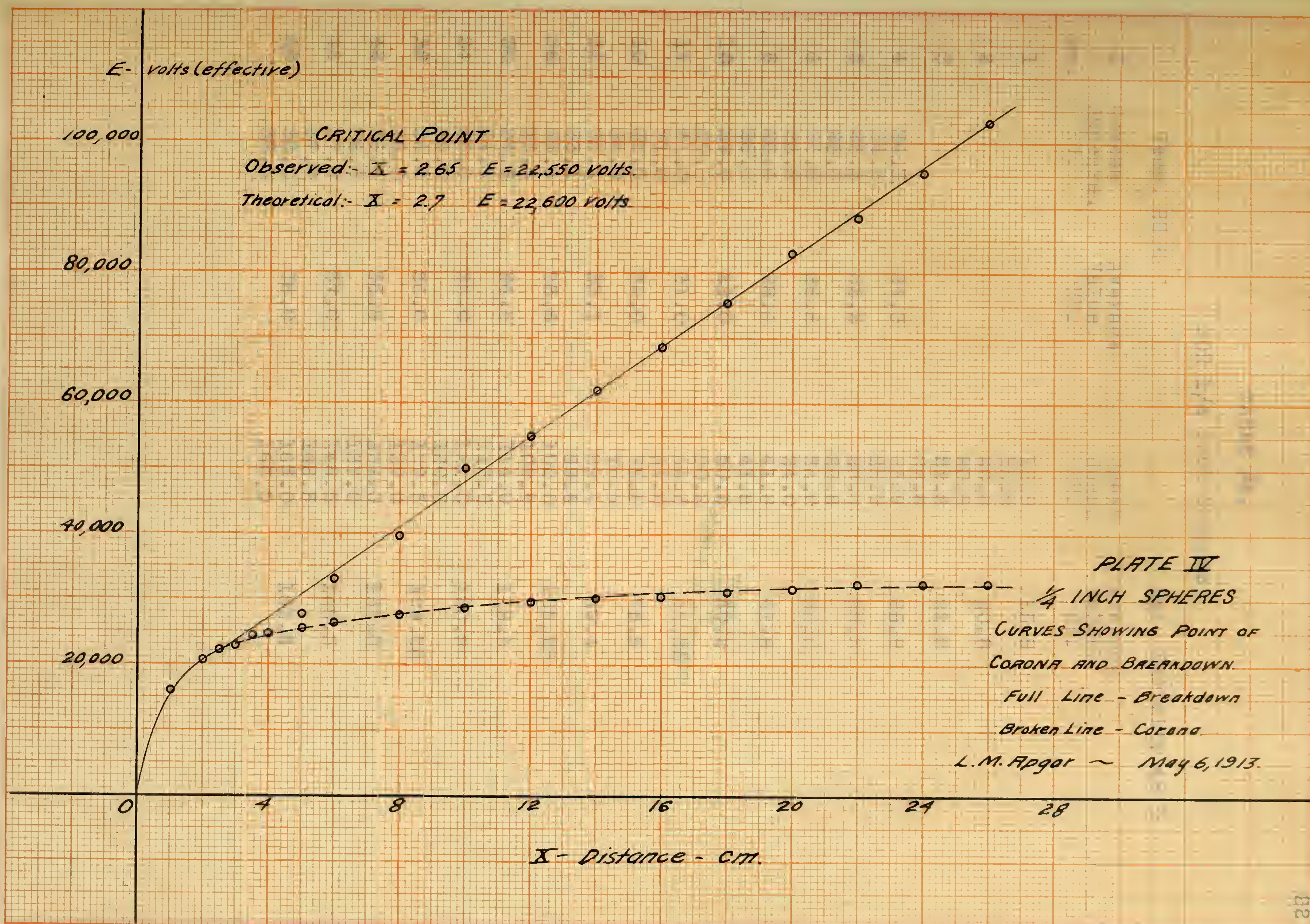
Plotting this critical point on Plate XI it is found that it practically falls upon the needle gap curve.

TABLE #3.

FOR 1/4 INCH SPHERES.

Temp. 26 C Rel. Humidity - 50 %

X cm.	Corona Appears KV.	Average Value KV.	Break down KV.	Average Value KV.	Notes
1.0				16.0	
2.0				20.6	
2.5				22.2	
3.0				23.2	
3.5				24.2	
4.0	24.6	24.6	25.2	25.2	
	24.6		25.2		
5.0		25.4		27.8	
6.0		26.4		33.0	
8.0		27.6		39.8	
10.0	29.0	28.9	50.0	50.0	polished
	28.6		50.0		not polished
12.0	29.4	29.4	55.0	55.0	polished
	29.4		55.0		not polished
				59.0	with fan
14.0	30.0	30.0	62.0	62.0	
	30.0		62.0		
16.0	30.5	30.25	69.5	68.75	
	30.0		68.0		
18.0		31.0	76.5	75.25	
			74.0		
20.0	31.5	31.5	83.0	83.0	polished
	31.5		83.0		not polished
				86.5	with fan
22.0	32.5	32.5	89.0	88.3	
	32.5		88.0		
			88.0		
24.0		32.5	96.0	95.5	
			95.0		
26.0	32.5	32.56	103.0	103.0	
	32.5		103.0		
	32.7				


E- volts (effective)
100,000
80,000
60,000
40,000
20,000
0
4
8
12
16
20
24
28
X - Distance - cm.
CRITICAL POINT
Observed:- X = 2.65 E = 22,550 volts.
Theoretical:- X = 2.7 E = 22,600 volts
PLATE IV
1/4 INCH SPHERES
CURVES SHOWING POINT OF
CORONA AND BREAKDOWN.
Full Line - Breakdown
Broken Line - Corona
L.M. Apgar ~ May 6, 1913.

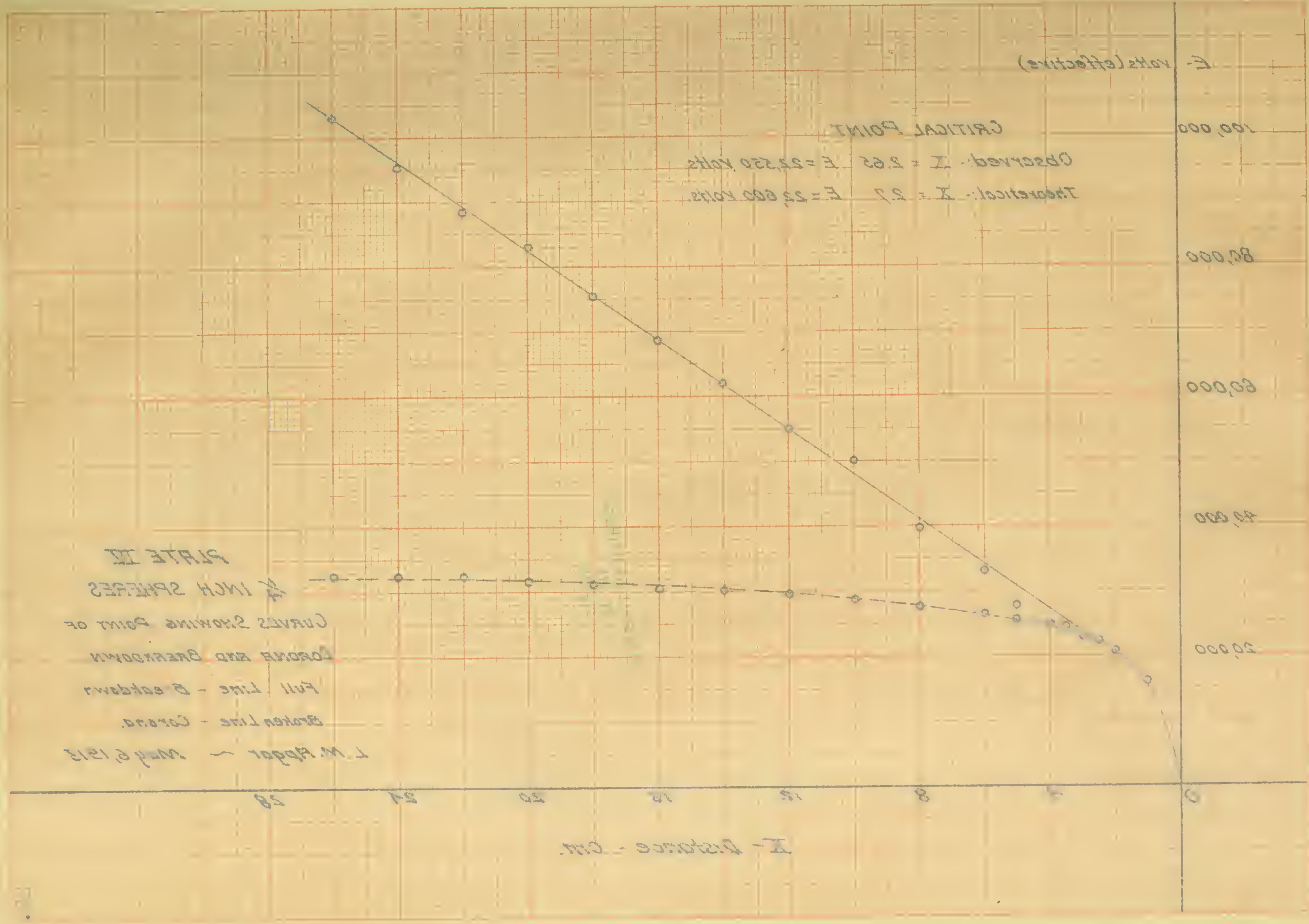


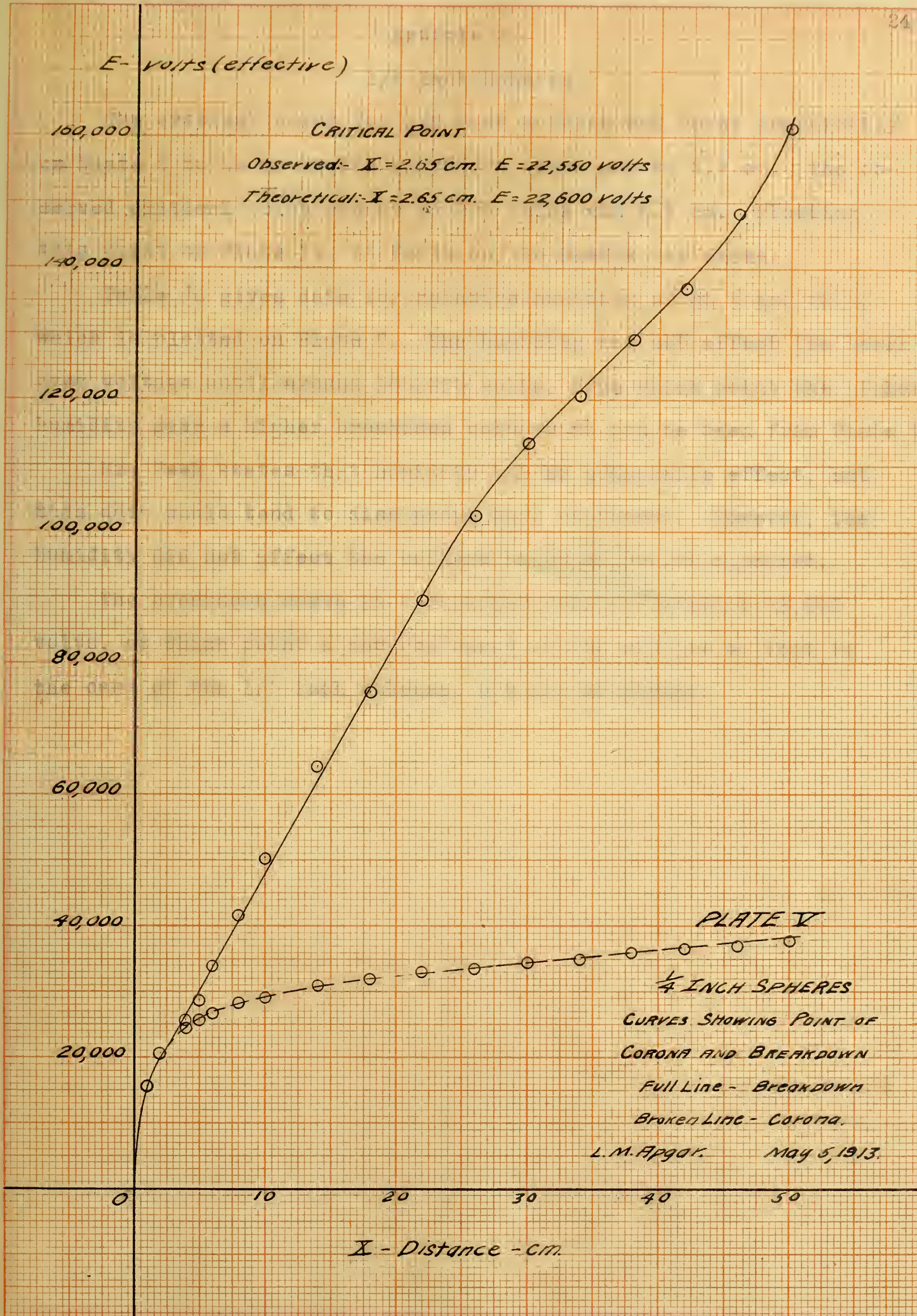
PLATE III
1/4 INCH SPHERES
Curves Showing Point of
Corona and Breakdown
Full Line - Breakdown
Broken Line - Corona.
L. M. Apgar — May 6, 1913
CRITICAL POINT
Observed:- X = 2.65 E = 22,550 volts
Theoretical:- X = 2.7 E = 22,600 volts.
E - volts (effective)
100,000
80,000
60,000
40,000
20,000
0
4
8
12
16
20
24
28
X - Distance - cm.

TABLE #4.

FOR 1/4 INCH SPHERES.

Temp. 23 C   Rel. Humidity 48 %

X cm.	Corona Appears. KV.	Average Value. KV.	Break down. KV.	Average Value. KV.
1			15.8	15.8
			15.8	
2			20.8	20.8
			20.8	
3			22.8	22.8
			22.8	
4	24.3	24.3	25.9	25.9
	24.3		25.9	
5	25.5	25.5	28.8	28.8
	25.5		28.8	
6	26.8	26.8	34.0	34.0
	26.8		34.0	
8	28.4	28.4	41.8	41.8
	28.4		41.8	
10	29.0	29.0	50.2	50.2
	29.0		50.2	
14	31.0	31.0	64.5	64.25
	31.0		64.0	
18	32.0	32.0	75.5	75.5
	32.0		75.5	
22	33.1	33.1	89.4	89.4
	33.1		89.4	
26	33.6	33.6	102.0	102.25
	33.6		102.5	
30	34.5	34.5	114.0	113.5
	34.5		113.0	
34	35.0	35.0	121.0	120.5
	35.0		120.0	
38	36.0	36.0	129.5	129.25
	36.0		129.0	
42	36.5	36.5	137.0	137.0
	36.5		137.0	
46	37.0	37.0	148.5	148.5
	37.0		148.5	
50	38.0	38.0	163.0	161.5
	38.0		160,0	



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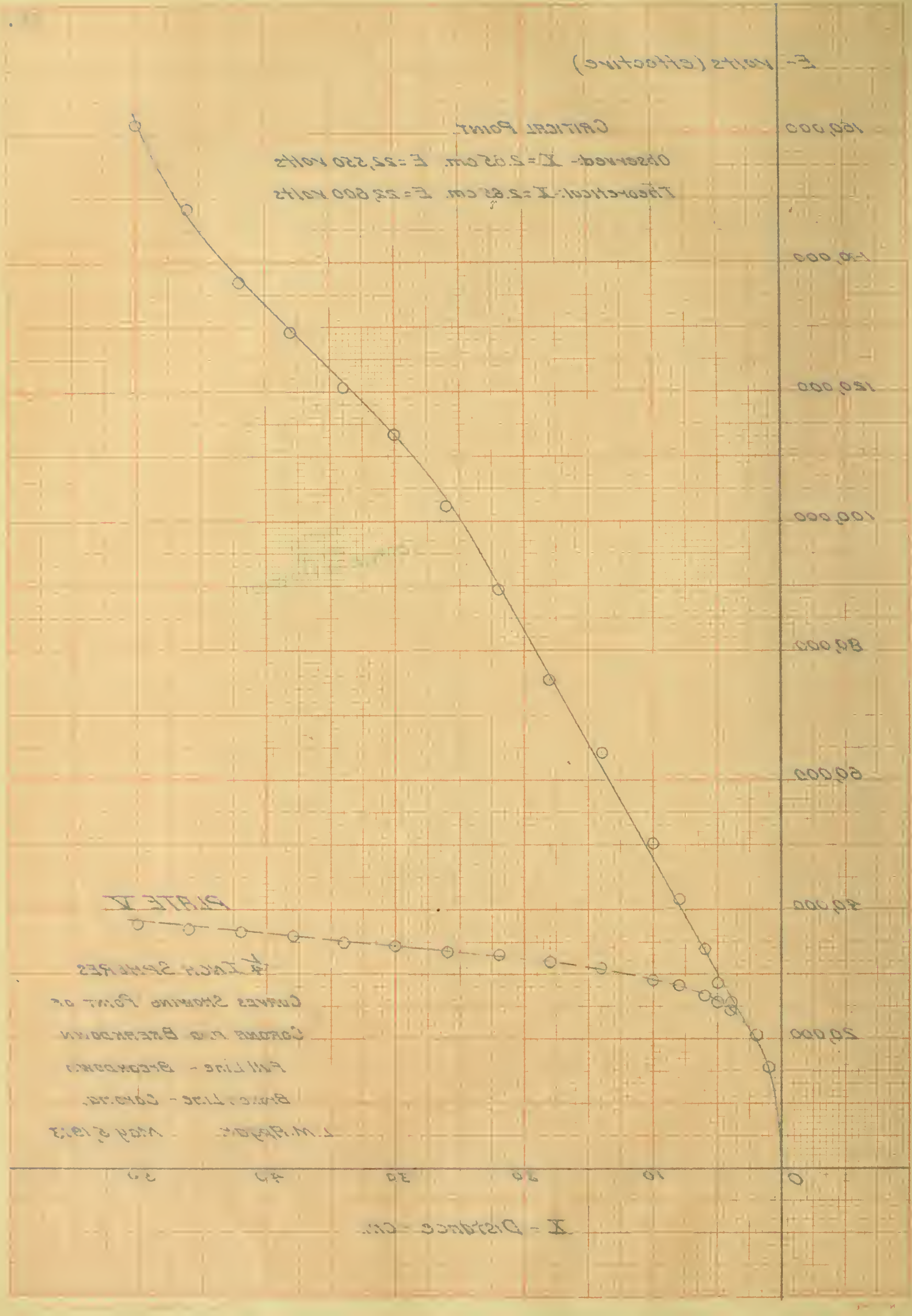

E - volts (effective)
CRITICAL POINT
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
10
20
30
40
50
X - Distance - Cm.

Article 3.

1/2 Inch Spheres.

The critical point for 1/2 inch spheres was found graphically on Plate 6 to be at 39,500 volts for spark gap of 5.7 cm. The observed critical point was at 40.000 volts and 5.7 cm. Plotting this point on Plate 11, it falls on the needle gap curve.

Table #6 gives data for relative humidity of 56 % and 40 %, which is plotted on Plate 7. The humidity did not affect the spark over voltage until around 100,000 volts, from which point the higher humidity gave a higher breakdown voltage as can be seen from Plate 7.

Mr. Peek states that humidity has no measurable effect, but this data would tend to disaprove that statement. However, the humidity did not affect the voltage at which corona appeared.

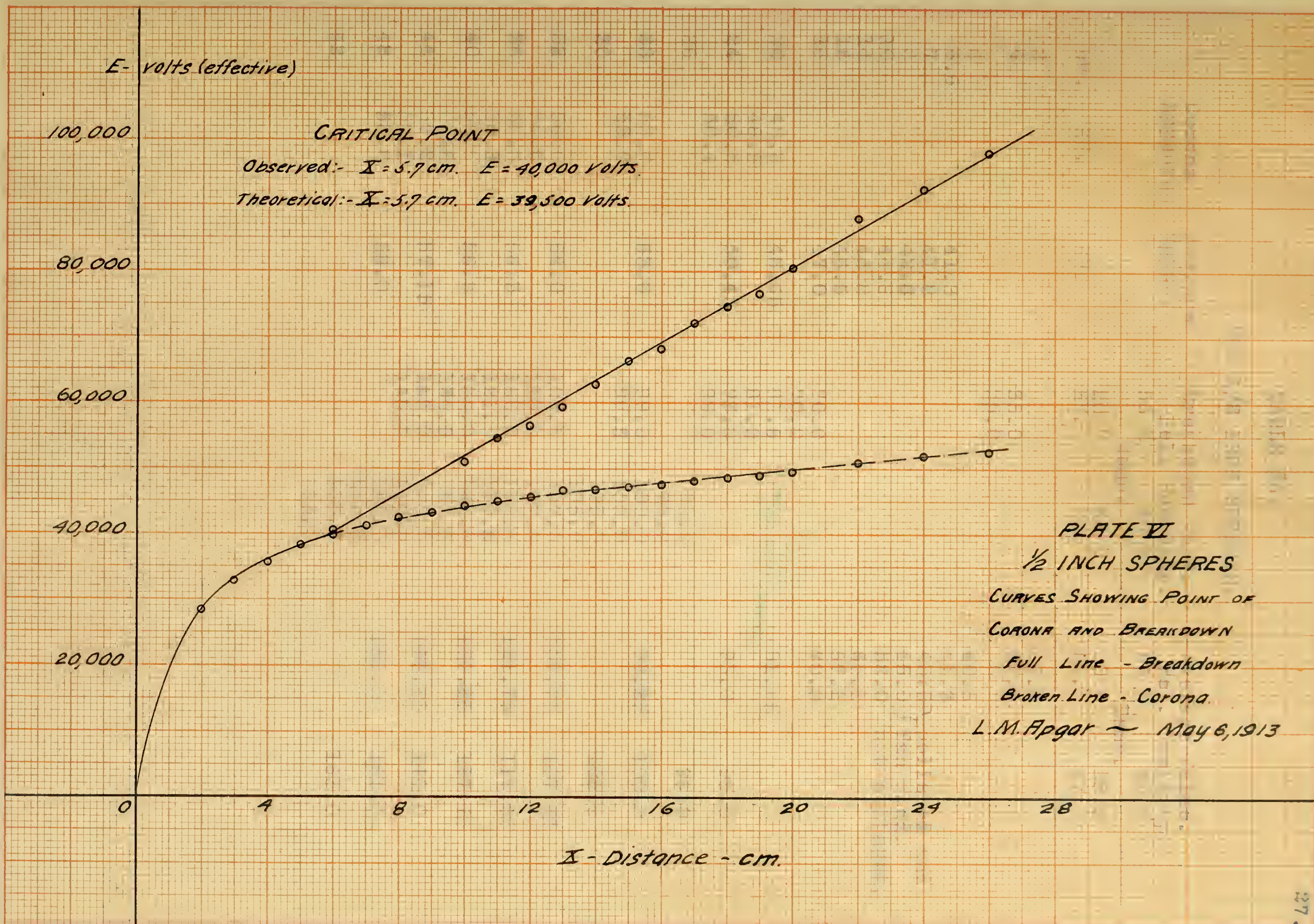
The breakdown curve is a straight line up to about 82,000 volts, at which point a reverse curve starts similar to that in the case of the 1/4 inch spheres, but not so marked.

TABLE #5.

FOR 1/2 INCH SPHERES.

Temp. 26 C. Rel. Humidity - 50 %

X cm.	Corona Appears KV.	Average Value KV.	Break-down KV.	Average Value KV.
2			28.4	28.4
			28.4	
3			32.8	32.9
			33.0	
4			36.0	35.75
			35.5	
5			38.2	38.1
			38.0	
6			40.0	40.0
			40.0	
7			41.0	41.2
			41.4	
8			42.0	42.15
			42.3	
9			43.5	43.2
10	44.0	44.2	51.0	51.0
	44.4		51.0	
11	44.5	45.0	54.5	54.75
	45.5		55.0	
12	45.0	45.5	56.5	56.25
	46.0		56.0	
13	46.2		59.5	59.5
			59.5	
14	46.8		63.0	62.5
			62.0	
15	47.0		66.5	66.25
			66.0	
16	47.5	47.4	68.0	68.0
	47.3		68.0	
17	48.0		72.0	
18	48.5		74.5	
19	49.0		76.5	
20	50.0	49.75	80.5	80.75
	49.5		81.0	
22	51.0		88.0	
24	51.9		92.5	92.5
			92.5	
26	52.5		98.0	98.0
			98.0	


E- volts (effective)
100,000
80,000
60,000
40,000
20,000
0
4
8
12
16
20
24
28
X - Distance - cm.
Critical Point
Observed:- X = 5.7 cm. E = 40,000 volts.
Theoretical:- X = 5.7 cm. E = 39,500 volts.
Plate VI
½ Inch Spheres
Curves Showing Point of
Corona and Breakdown
Full Line - Breakdown
Broken Line - Corona
L. M. Apgar ~ May 6, 1913

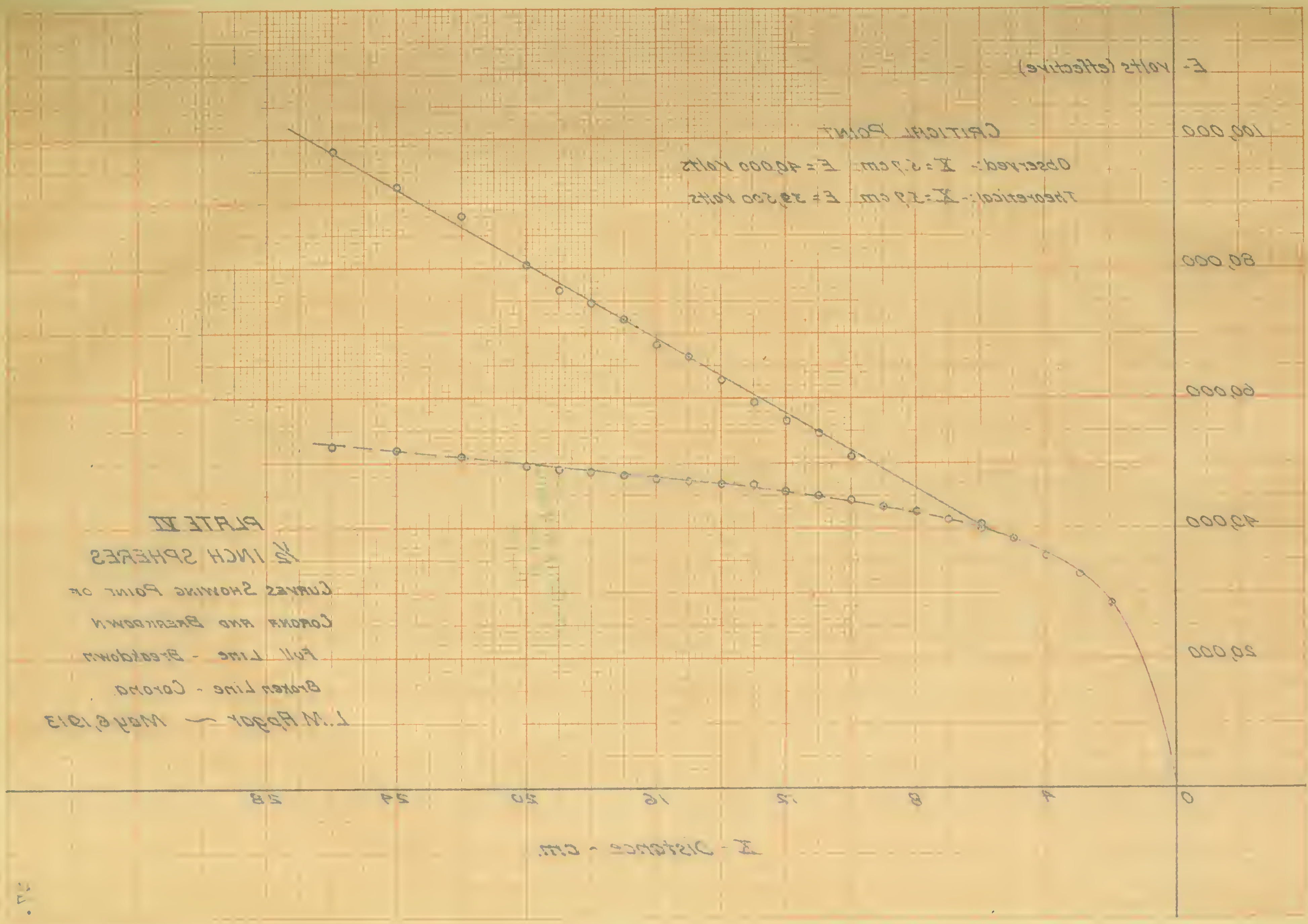
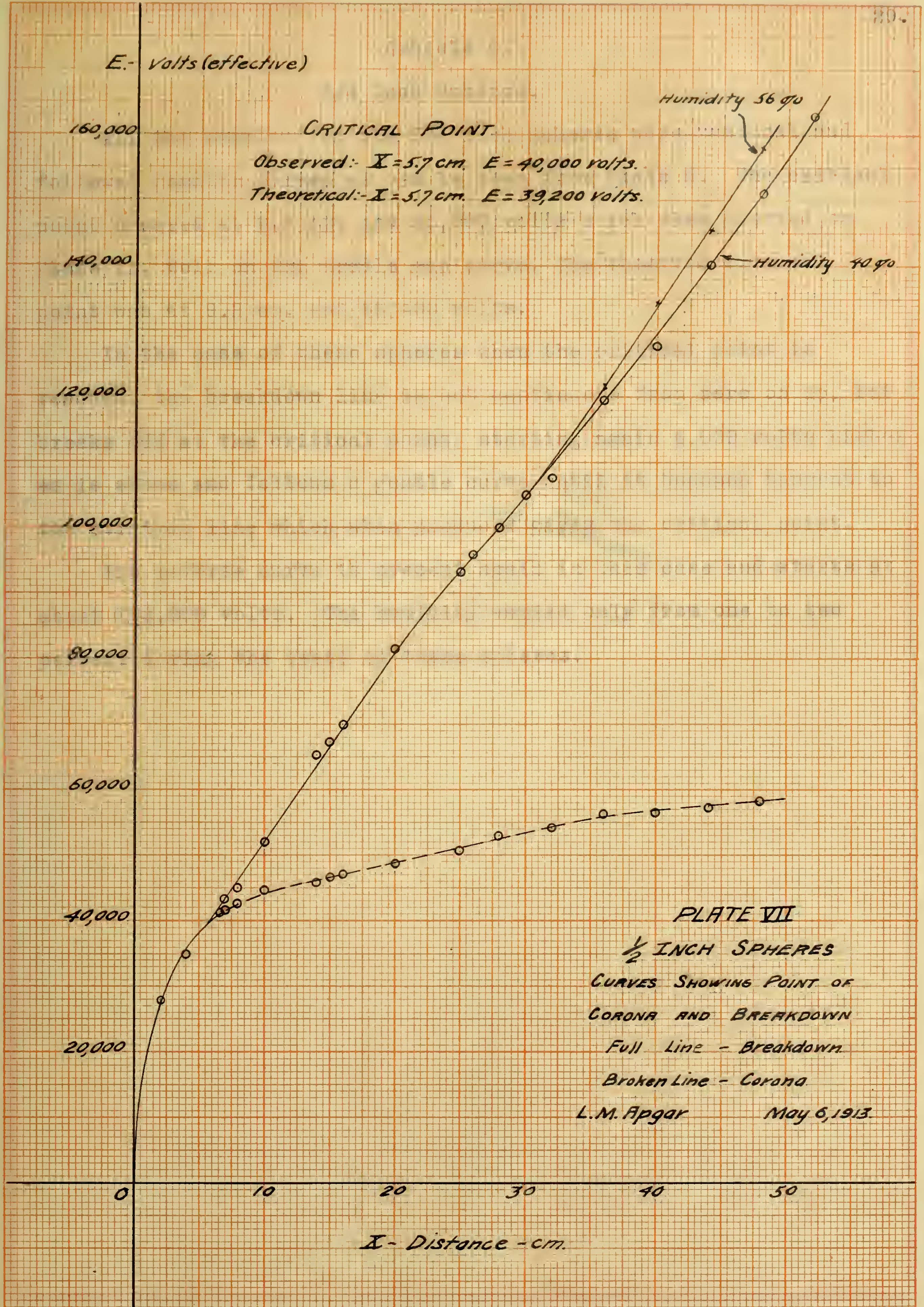


PLATE VI
½ INCH SPHERES
Curves Showing Point of
Corona and Breakdown
Full Line - Breakdown
Broken Line - Corona
L. M. Rogar — May 6, 1913
CRITICAL POINT
Observed:- X = 5.7 cm. E = 40,000 volts
Theoretical:- X = 5.9 cm. E = 39,500 volts
E - volts (effective)
100,000
80,000
60,000
40,000
20,000
0
4
8
12
16
20
24
28
X - Distance - cm.

TABLE #6.

FOR 1/2 INCH SPHERES.

	Corona Appears.	Average Value.	Breakdown Volt. Rel. Humidity. 56 % Temp. 20 C	Breakdown Volt. Rel. Humidity. 40 % Temp. 23 C	Average Value. Rel. Humidity. 56 % Temp. 20 C	Average Value. Rel. Humidity. 40 % Temp. 23 C	
cm.	KV.	KV.	KV.	KV.	KV.	KV.	
2					28.0		
4			35.0		35.0		
			35.0				
6					40.5		
6.6		41.3			41.3		
7		41.8			43.5		polished and
8		42.8			45.0		fan used.
10		44.8			52.0		not polished.
14		45.8			65.1		
15		46.5			67.2		
16		47.0	70.0		70.0		
			70.0				
20	48.8	48.65	81.5		81.25		
	48.5		81.0				
24	50.5	50.45	93.0		93.0	93.0	
	50.4		93.0				
26				96.0		96.0	
				96.0			
28	53.0	53.0	99.0	100.0	99.25	100.0	
	53.0		99.5	100.0			
30				105.0		105.0	
				105.0			
32	54.0	54.0	109.5	107.0	109.75	107.25	
	54.0		110.0	107.5			
36	56.3	56.3	122.0	119.6	121.75	119.55	
	56.3		121.5	119.5			
40	56.5	56.5	134.0	128.0	134.25	127.75	
	56.5		134.5	127.5			
44	57.2	57.15	145.0	140.0	145.25	140.0	
	57.1		145.5	140.0			
48	58.0	58.0		151.0	158.0	151.0	
				151.0			
52				163.0		163.0	
				163.0			



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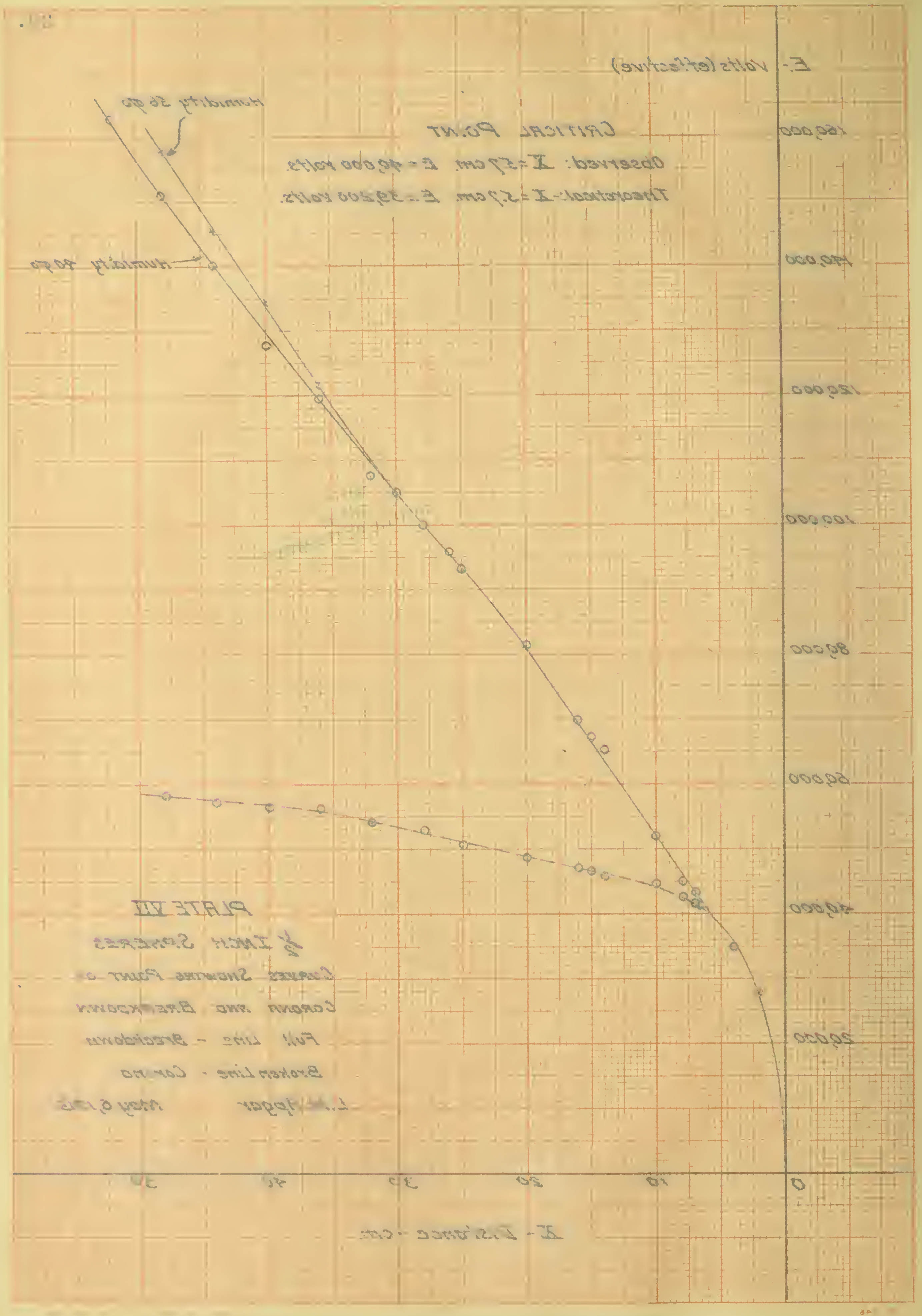

E - volts (effective)
Critical Point
Observed: X = 5.7 cm. E = 46,000 volts.
Theoretical: X = 5.7 cm. E = 39,200 volts.
Humidity
Humidity
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
10
20
30
40
50
X - Distance - cm.
PLATE VII
1/2 Inch Spheres
Curves Showing Point of
Corona and Breakdown
Full Line - Breakdown
Broken Line - Corona

Article 4.

3/4 Inch Spheres.

All the results for the 3/4 inch spheres were rational and followed regular curves as can be seen from Plate 8. The critical point occured at 9.3 cm. and 55,000 volts which when plotted on Plate 11. fell on the needle gap curve. The observed critical point was at 9.2 cm. and 55,400 volts.

In the case of these spheres when the critical point is reached, the breakdown line is not continuous from zero on up, but breaks off at the critical point, starting again 4,000 volts higher as is shown and follows a gentle curve until it becomes tangent to the straight line which when produced gives the critical point.

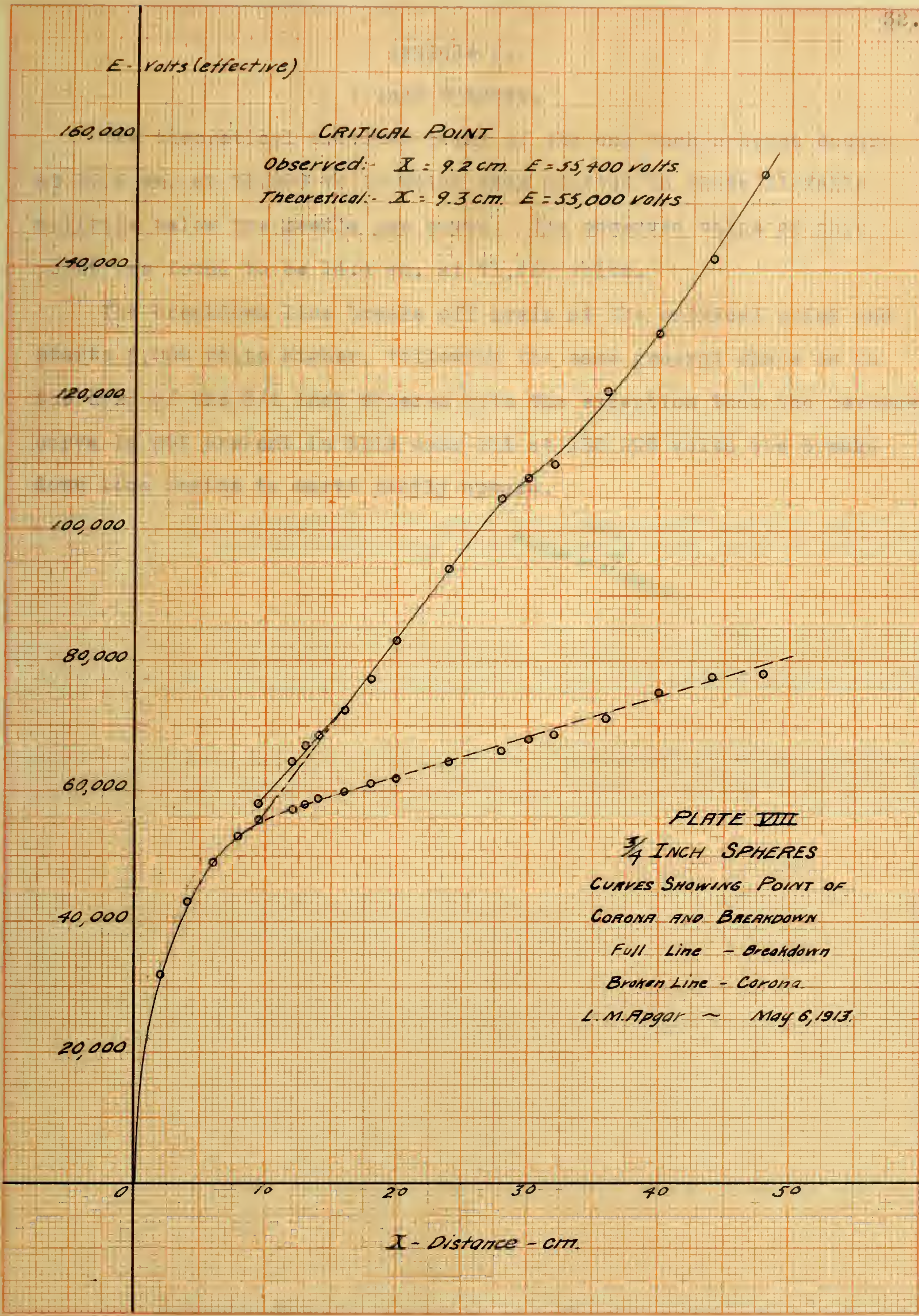
The reverse curve is present again in this case and starts at about 102,000 volts. The humidity varied only from one to two percent during the tests on these spheres.

TABLE #7.

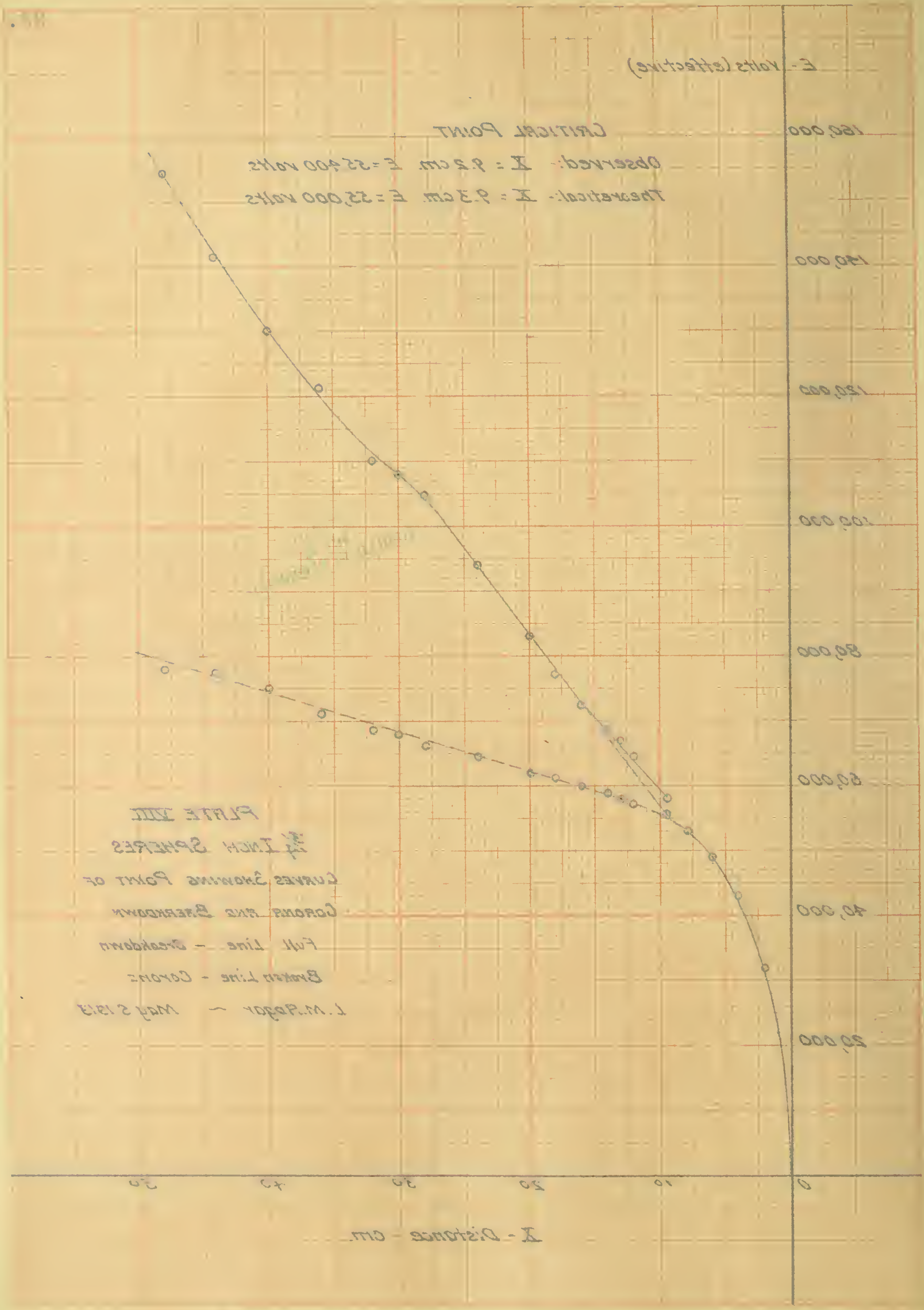
FOR 3/4 INCH SPHERES.

Temp. 22 C. Relative Humidity - 48 %

X cm.	Corona Appears. KV.	Average Value. KV.	Break-down. KV.	Average Value. KV.	Notes
2				32.0	
4				43.2	
6				49.0	
8				53.0	
9				54.0	
9.2				55.4	
9.25		55.5		56.6	
9.3		55.6		57.6	
9.5		55.9		58.0	
10	56.2				
11	56.5				
12	57.2	57.2	65.0	64.5	
	57.2		64.0		
			57.0		polished,& fan used
			57.0		but no corona.
12.5	57.5	57.5	64.0	64.9	
	57.5		65.8		
13	58.0	58.0	67.5	67.0	not polished.
	58.0		66.5		flashed before cor.
			67.0		
14	59.0	59.0	68.7	68.65	No flash
	59.0		68.6		
16	60.0	60.0	72.5	72.5	
	60.0		72.5		
18	61.2	61.2	77.0	77.0	
	61.2		77.0		
20	62.0	62.0	83.0	83.0	
	62.0		83.0		
24	64.5	64.5	94.5	94.5	
	64.5		94.5		
28	66.2	66.25	105.0	105.0	
	66.3		105.0		
				108.5	with fan
30	68.0	68.0	108.0	108.0	
	68.0		108.0		
32	68.9	68.9	110.0	110.0	
	68.9		110.0		
36	71.0	71.0	121.0	121.25	
	71.0		121.5		
40		75.0	130.0	130.0	
			130.0		
44		77.5	141.0	141.5	
			142.0		
48		78.0	154.0	154.6	
			156.0		
			154.0		


E - Volts (effective)
CRITICAL POINT
Observed:- X = 9.2 cm. E = 55,400 volts.
Theoretical:- X = 9.3 cm. E = 55,000 volts
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
10
20
30
40
50
X - Distance - cm.
PLATE VIII
3/4 INCH SPHERES
CURVES SHOWING POINT OF
CORONA AND BREAKDOWN
Full Line - Breakdown
Broken Line - Corona
L. M. Apgar ~ May 6, 1913.

NO. 346


E - volts (effective)
CRITICAL POINT
Observed: X = 9.2 cm. E = 55,400 volts
Theoretical: X = 9.3 cm. E = 55,000 volts
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
10
20
30
40
50
X - Distance - cm.
PLATE XIII
Inch Spheres
Curves Showing Point of
Corona and Breakdown
Full Line - Breakdown
Broken Line - Corona

Article 5.

1 Inch Spheres.

The theoretical critical point of the one inch spheres occurs at 14.4 cm. at 71,000 volts which when plotted on Plate 11 falls a little below the needle gap curve. The observed value of this point was found to be 14.4 cm. at 71,450 volts.

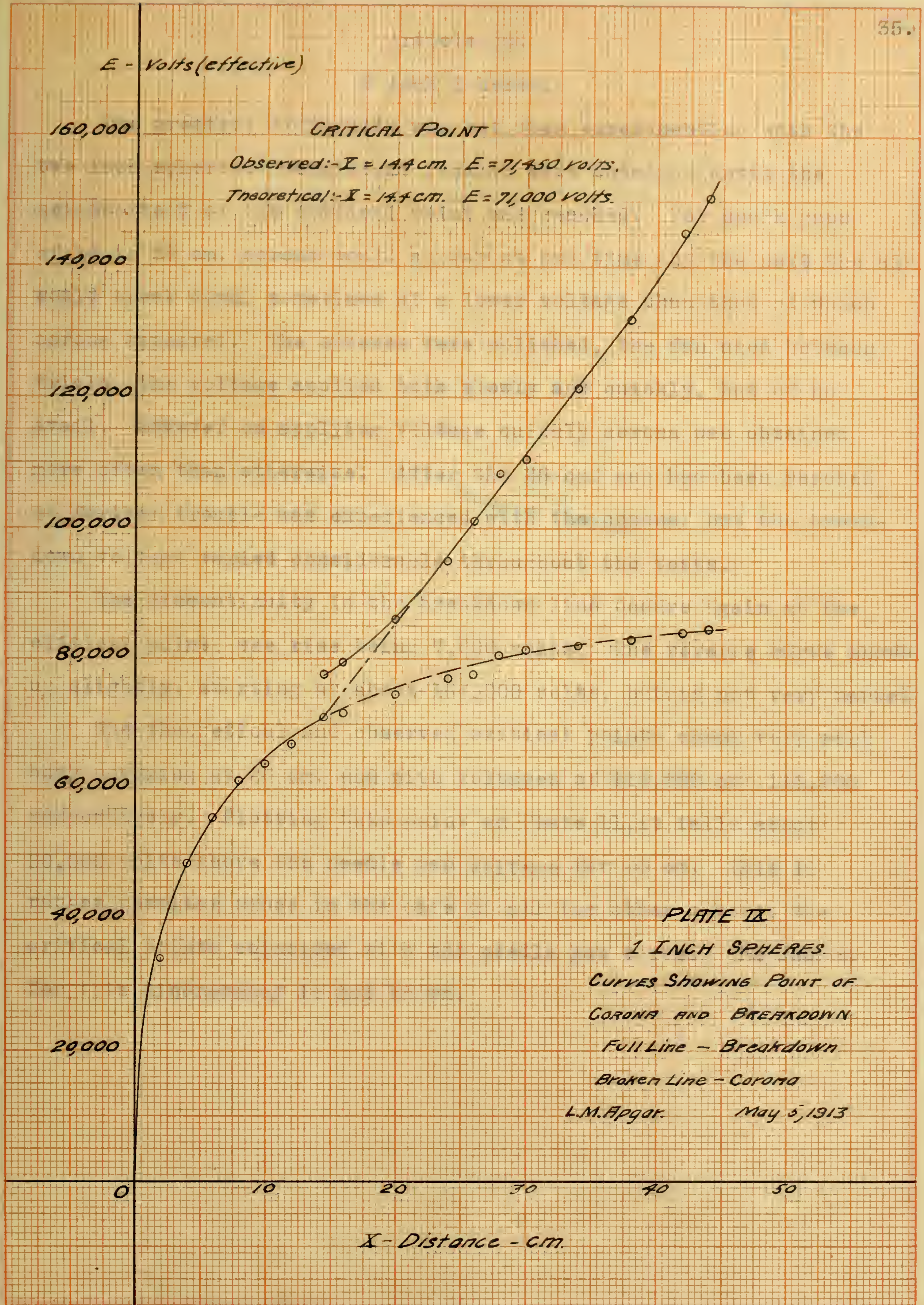
The breakdown line breaks off again at the critical point and starts 6,000 volts higher, following the same general shape as in the case of the 3/4 inch spheres with the exception that the reverse curve is not present in this case but at 130,000 volts the break-down line begins to curve gently upward.

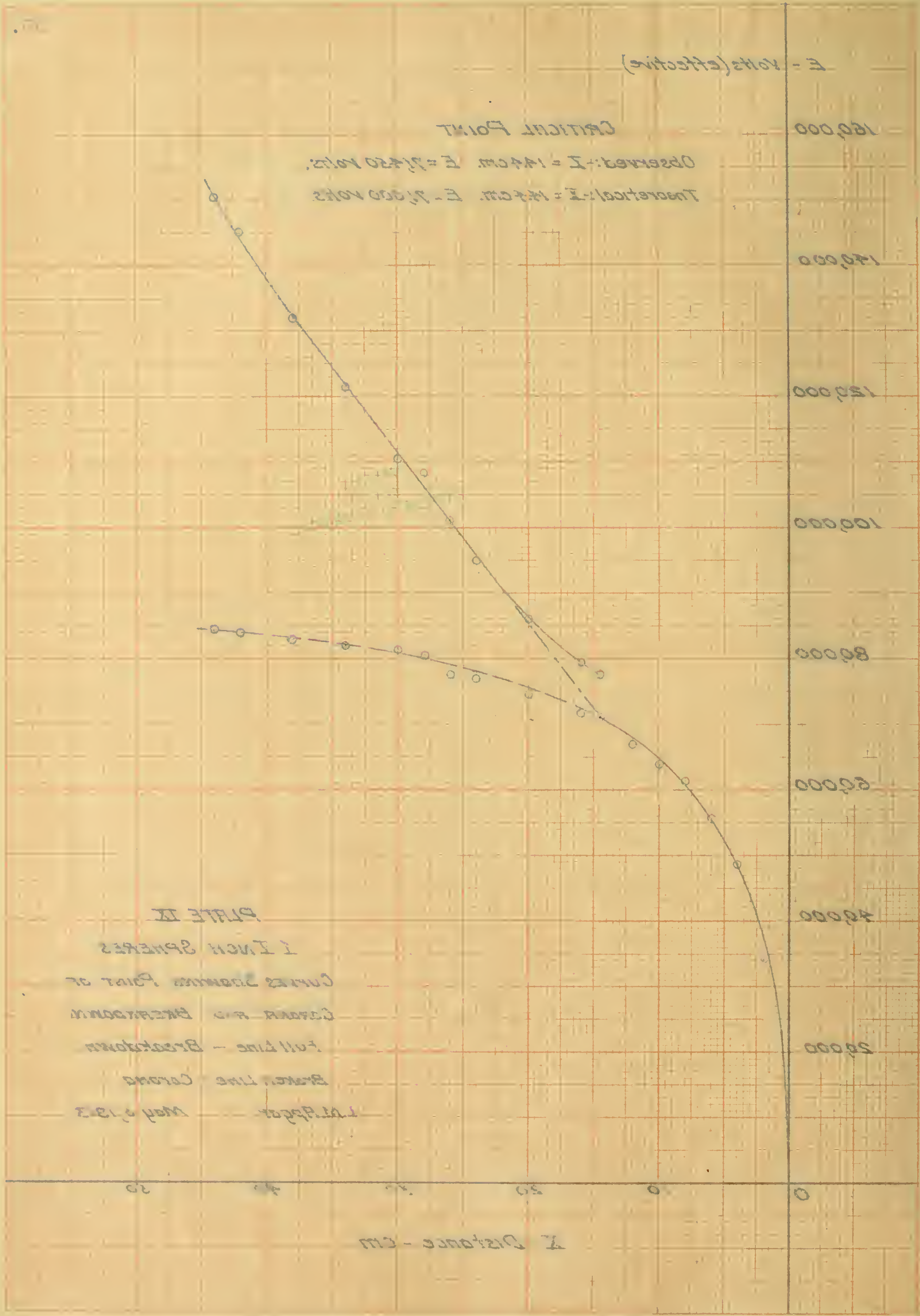
TABLE #8.

FOR 1 INCH SPHERES.

Temp.26 C — Relative Humidity - 56 %

X cm.	Corona Appears. KV.	Average Value. KV.	Break-down. KV.	Average Value. KV.	Notes
2			34.0	34.0	
4			48.5	48.75	
			49.0		
6			55.7	55.7	
			55.7		
8			61.5	61.25	
			61.0		
10			64.0	64.0	
			64.0		
12			66.5	67.0	
			67.5		
14.5		71.5		77.8	
14.7	71.5	71.55	78.0	77.9	
	71.6		77.8		
16	71.6	71.6	79.5	79.5	
	71.6		79.5		
20	74.5	74.5	86.0	86.0	polished
	74.5		86.0		not polished
24	77.0	77.0	95.0	95.0	polished
	77.0		95.0		not polished
26	77.5	77.5	100.0	101.0	polished
	77.5		102.0		not polished
28	80.5	80.5	108.5	108.25	polished
	80.5		108.0		not polished
30	81.5	81.5	112.0	110.3	polished
	81.6		110.0		not polished
			109.0		" "
34	82.0	82.0	121.0	121.25	polished
	82.0		121.5		not polished
38	83.0	83.0	132.0	132.0	polished
	83.0		132.0		not polished
42	84.0	84.0	146.0	145.3	
	84.0		145.0		
			145.0		
44	84.2	84.2	151.0	150.5	
	84.2		150.0		


E - Volts (effective)
CRITICAL POINT
Observed:- X = 14.4 cm. E = 71,450 volts.
Theoretical:- X = 14.4 cm. E = 71,000 volts.
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
10
20
30
40
50
X - Distance - cm.
PLATE IX
1 INCH SPHERES.
CURVES SHOWING POINT OF
CORONA AND BREAKDOWN
Full Line - Breakdown
Broken Line - Corona
L.M. Apgar. May 5, 1913


E - Volts (effective)
CRITICAL POINT
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
10
20
30
40
50
L Distance - cm
1 Inch Spheres
Full Line - Breakdown

Article #6.

2 Inch Spheres.

The greatest difficulty was met when experimenting with the two inch spheres. Consistent results were obtained until the neighborhood of the critical point was reached. For spark gaps of 18 to 28 cm. corona would appear at one time and the next the air would break down, sometimes at a lower voltage than that at which corona appeared. The spheres were polished, the fan used between trials, the voltage applied both slowly and quickly, but of no avail. However on applying voltage quickly corona was obtained more often than otherwise. After the 28 cm. gap had been reached no further trouble was experienced with the corona, but the breakdown voltage varied considerable throughout the tests.

The discontinuity in the breakdown line occurs again at the critical point, the rise being 7,000 volts. The reverse curve shows up slightly, starting at about 164,000 volts, but is not very marked

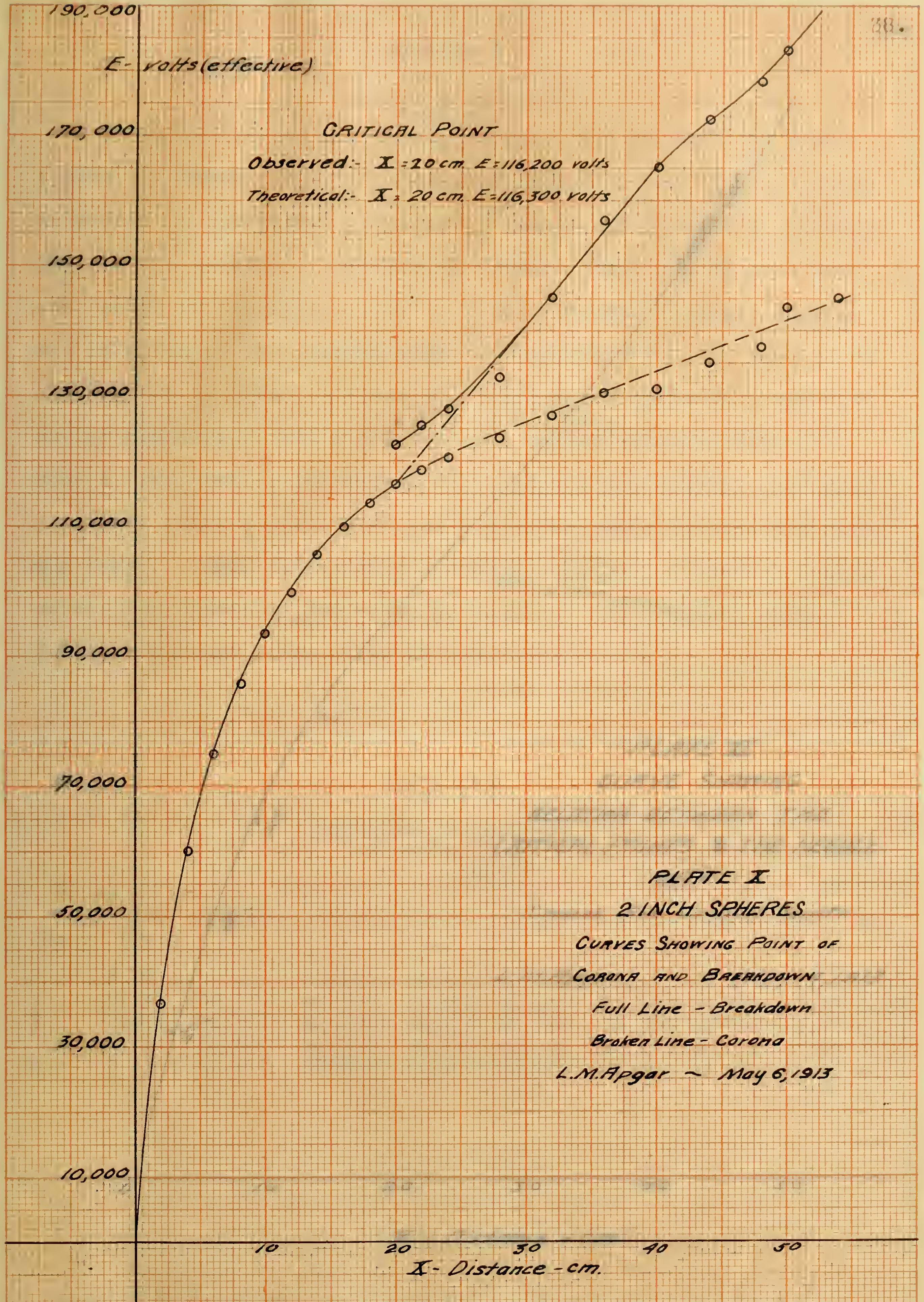
The theoretical and observed critical points check very well both occuring at 20 cm. and with voltages of 116,300 and 116,200 respectively. Plotting this point on Plate 11, it falls about 30,000 volts above the needle gap voltage for 20 cm. This is rather peculiar since in the case of all the other spheres the critical points coincided with the needle gap curve. The reason for this discrepancy is not known.

TABLE #9.

FOR 2 INCH SPHERES.

Temp. 25 C. Relative Humidity - 49 %

X cm.	Corona Appears. KV.	Average Value. KV.	Break-down. KV.	Average Value. KV.	Notes
2			36.6	36.6	
			36.6		
4			60.0	60.0	
			60.0		
6			75.0	75.0	
			75.0		
8			85.9	85.95	
			86.0		
10			93.2	93.35	
			93.5		
12			99.2	99.85	
			100.5		
14			105.8	105.8	
			105.8		
16			110.0	110.0	
			110.0		
18			113.5	113.5	
			113.5		
20	116.5	116.5	123.2	122.6	
	116.5		122.0		
22	119.0	118.75	124.0	125.25	polished
	118.5		126.5		
24	120.0	120.5	128.0	128.0	
	121.0		128.0		polished
28	124.0	123.5	133.0	132.75	not polished
	123.0		132.5		
32	127.0	127.0		145.0	
	127.0				
36	130.0	130.25	157.0	157.0	
	130.5		157.0		
40	131.0	131.0	165.0	165.0	
	131.0		165.0		
44	135.0	135.0	174.0	172.7	
	135.0		171.0		
			172.0		
48		137.5	181.0	178.0	
			175.0		
50		143.5	183.0	183.0	
			183.0		
54	145.5	145.5	193.0	193.0	
	145.5		193.0		
56	147.0	147.0	198.0	199.0	
	147.0		200.0		



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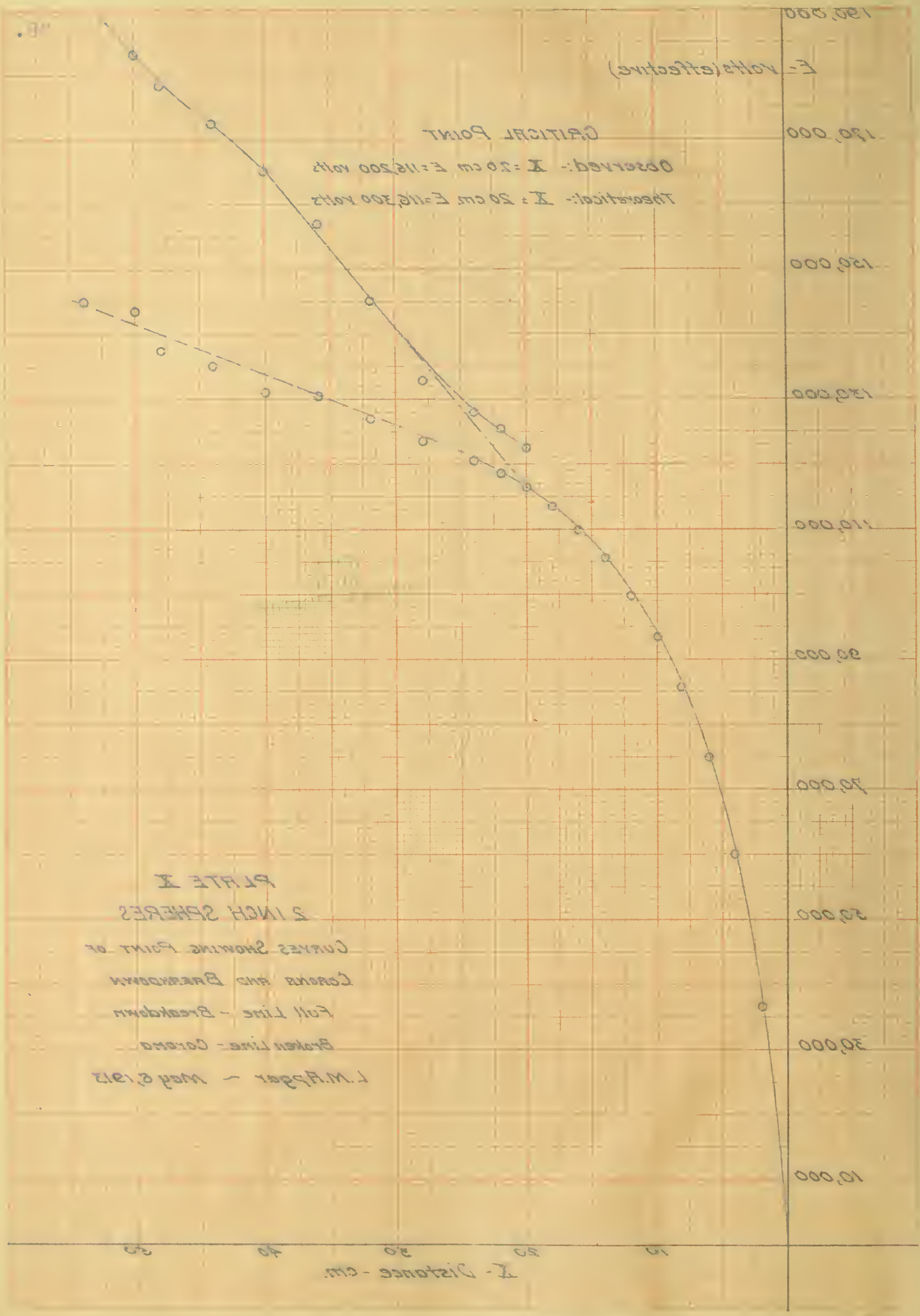
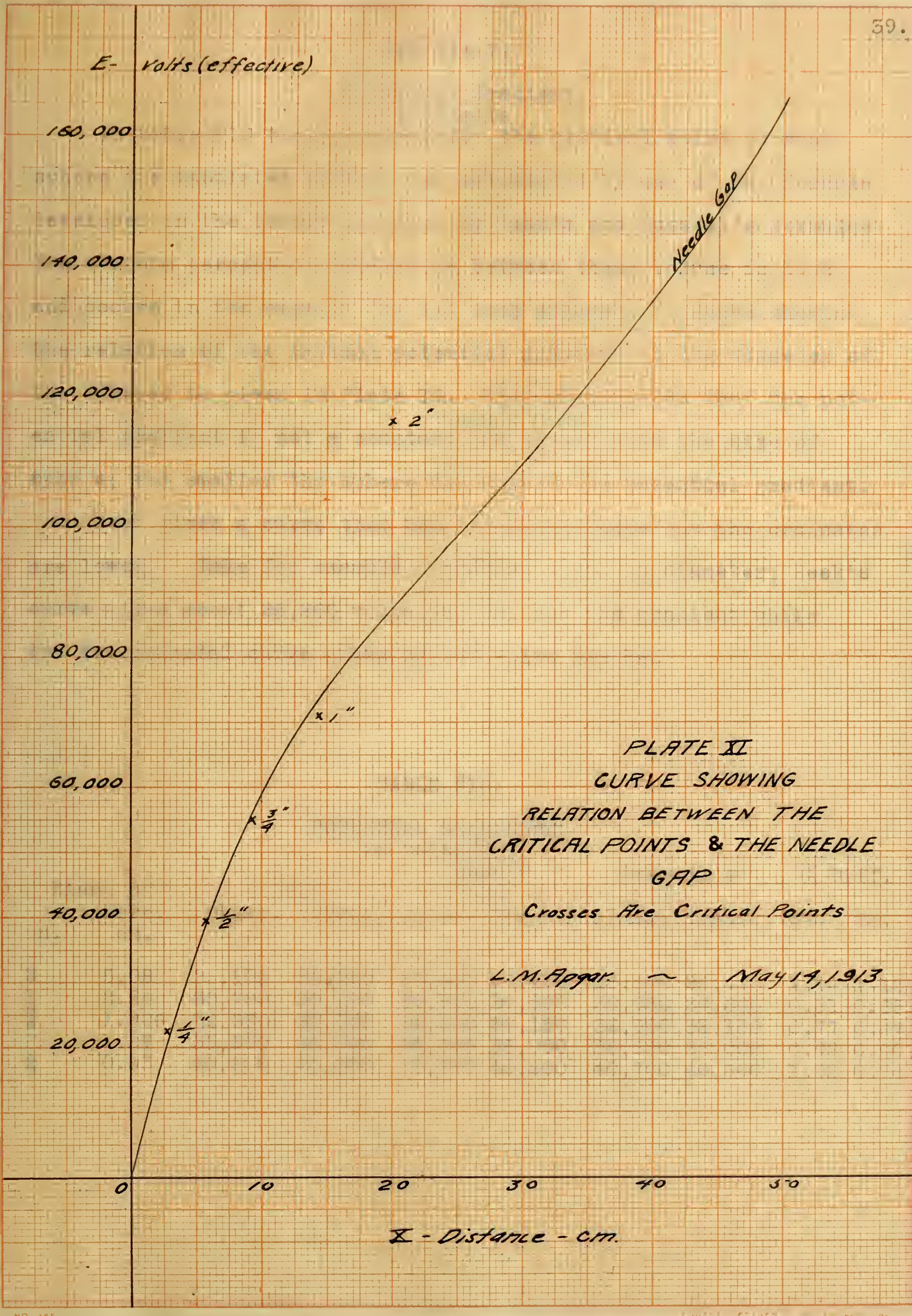
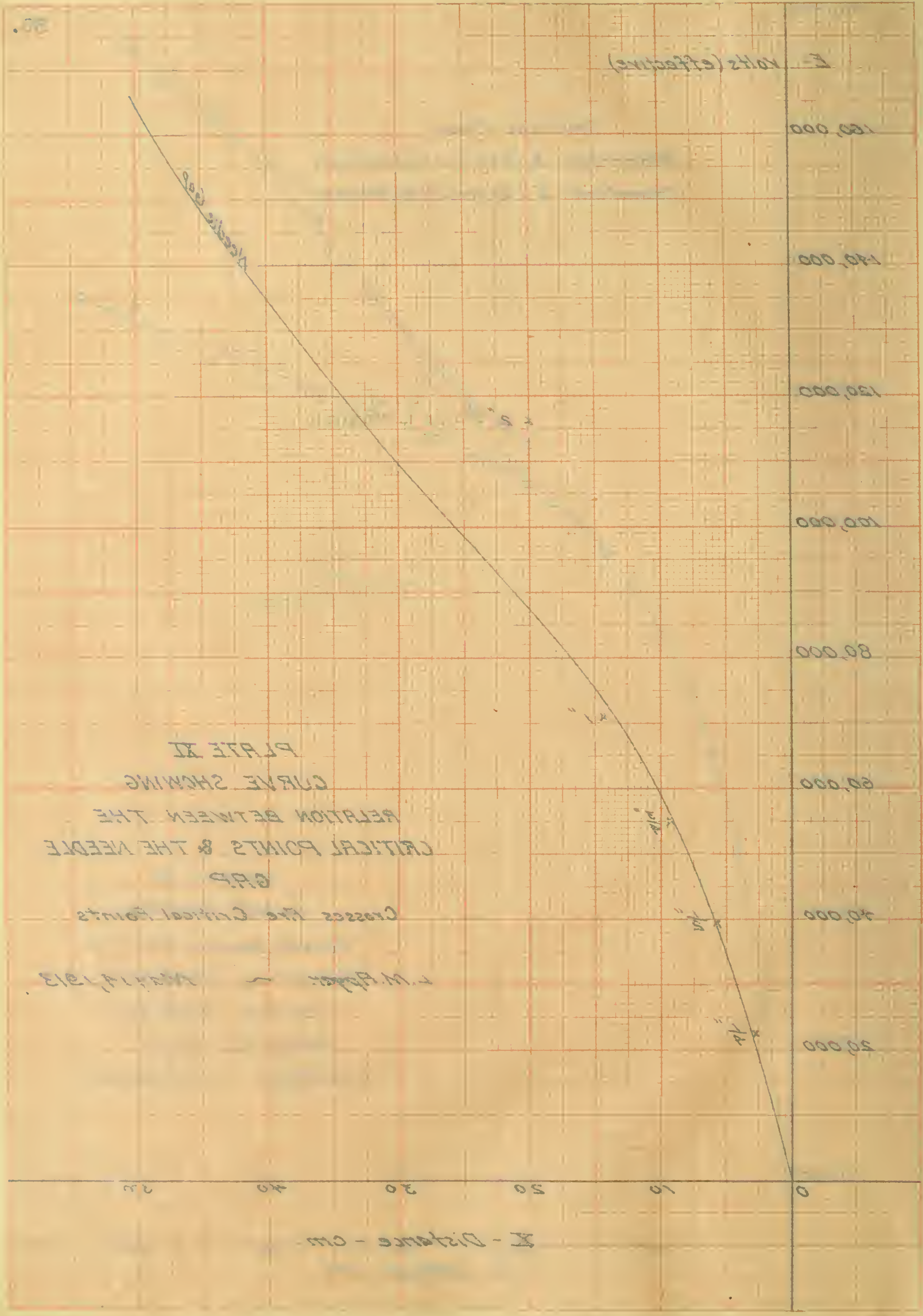


E - volts (effective)
CRITICAL POINT
Observed:- X = 20 cm E = 115,200 volts
Theoretical:- X = 20 cm E = 116,300 volts
190,000
170,000
150,000
130,000
110,000
90,000
70,000
50,000
30,000
10,000
50
40
30
20
10
X - Distance - cm.
PLATE X
2 INCH SPHERES
Curves Showing Point of Corona and Breakdown
Full Line - Breakdown
Broken Line - Corona
L.M. Apgar — May 6, 1913


E- volts (effective)
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
10
20
30
40
50
X - Distance - cm.
Needle Gap
2"
1"
3/4"
1/2"
1/4"
PLATE XI
CURVE SHOWING
RELATION BETWEEN THE
CRITICAL POINTS & THE NEEDLE
GAP
Crosses Are Critical Points
L.M. Apgar. ~ May 14, 1913


E - volts (effective)
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
10
20
30
40
X - Distance - cm.
Needle Gap
PLATE XI
CURVE SHOWING
RELATION BETWEEN THE
CRITICAL POINTS & THE NEEDLE
GAP
Crosses the Critical Points
May 14, 1913

Article 7.

Potential Gradient.

In table #10 the potential gradients for the critical point of each sphere are tabulated having been calculated by use of the formula developed in the theory and also by Dean's and Russell's formulae. The maximum percent of difference between these values is 1.22 and occurs in the case of the 1/4 inch spheres. A curve showing the relation of the maximum potential gradient to the diameter of the spheres is given in Plate 12. This curve shows that the potential gradient is not a constant but varies with the size of sphere; the smaller the sphere the higher the potential gradient.

Peek gives a curve that has a similar shape but the ordinates are lower. Take for example a sphere, 4 cm. in diameter; Peek's curve gives about 25,200 volts per cm. for the gradient while the experimental curve gives 27,800 volts per cm.

TABLE #10.

POTENTIAL GRADIENTS.
in volts/cm.

Diam. of Sphere. In.	Diam. of Sphere. cm.	f. Obser.	f. Theor.	Dean's f. Obser.	Dean's f. Theor.	Russell's f. Obser.	Russell's f. Theor.	% Diff. Ob.	% Diff. Th.
2	5.08	26,100	26,120	26,400	26.420	26,400	26,420	1.14	1.13
1	2.54	30,700	30,600	30,950	30,800	30,950	30,800	0.81	0.65
3/4	1.906	32,350	32,000	32,600	32,150	32,600	32,150	0.77	0.47
1/2	1.27	35,300	35,000	35,650	35,000	35,650	35,000	0.98	0.00
1/4	0.63	40,2 0	40,300	40,700	40,600	40,700	40,600	1.22	0.74

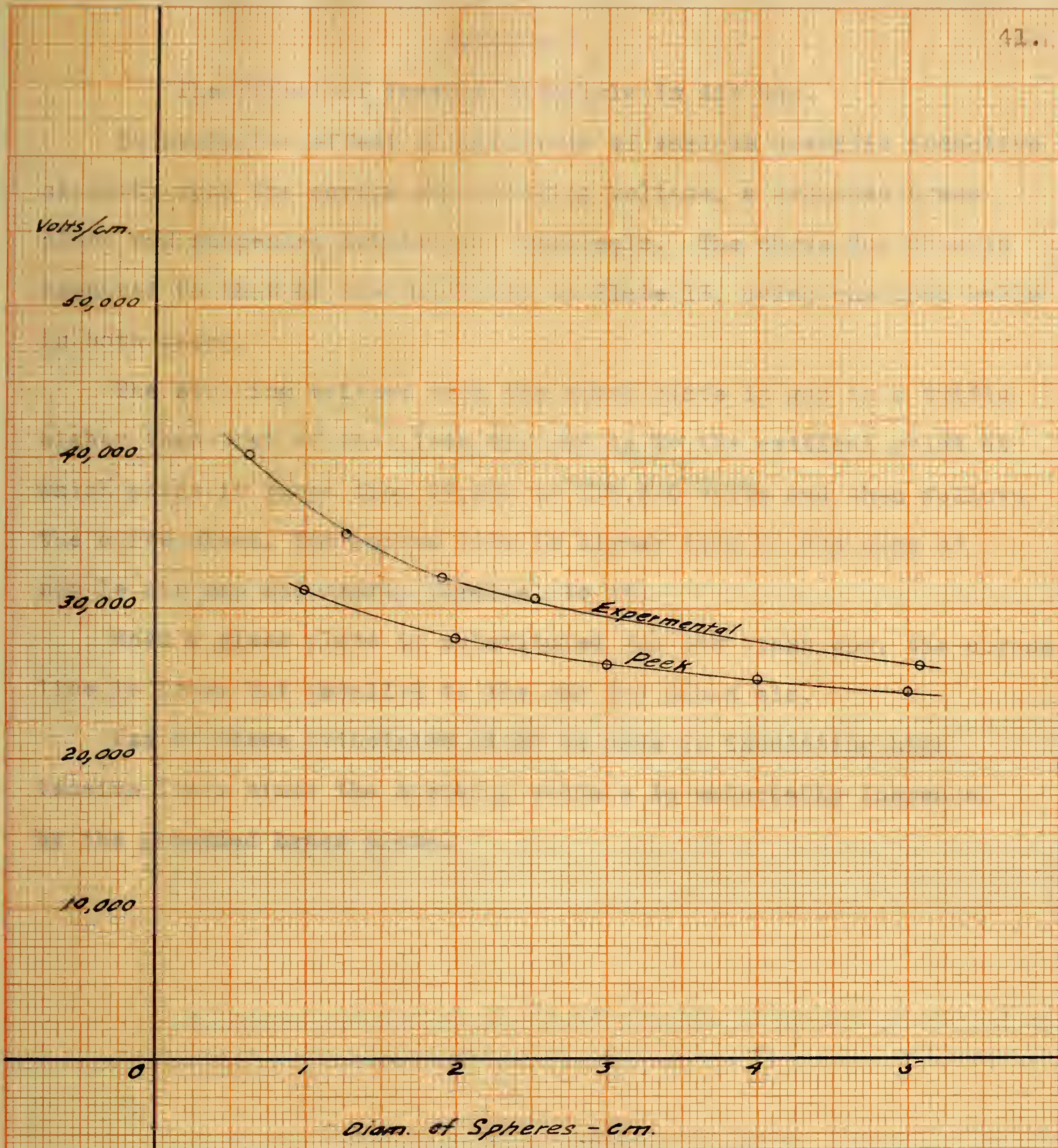


PLATE XII
COMPARISON OF
POTENTIAL GRADIENTS
L. M. Apgar — May 19, 1913.

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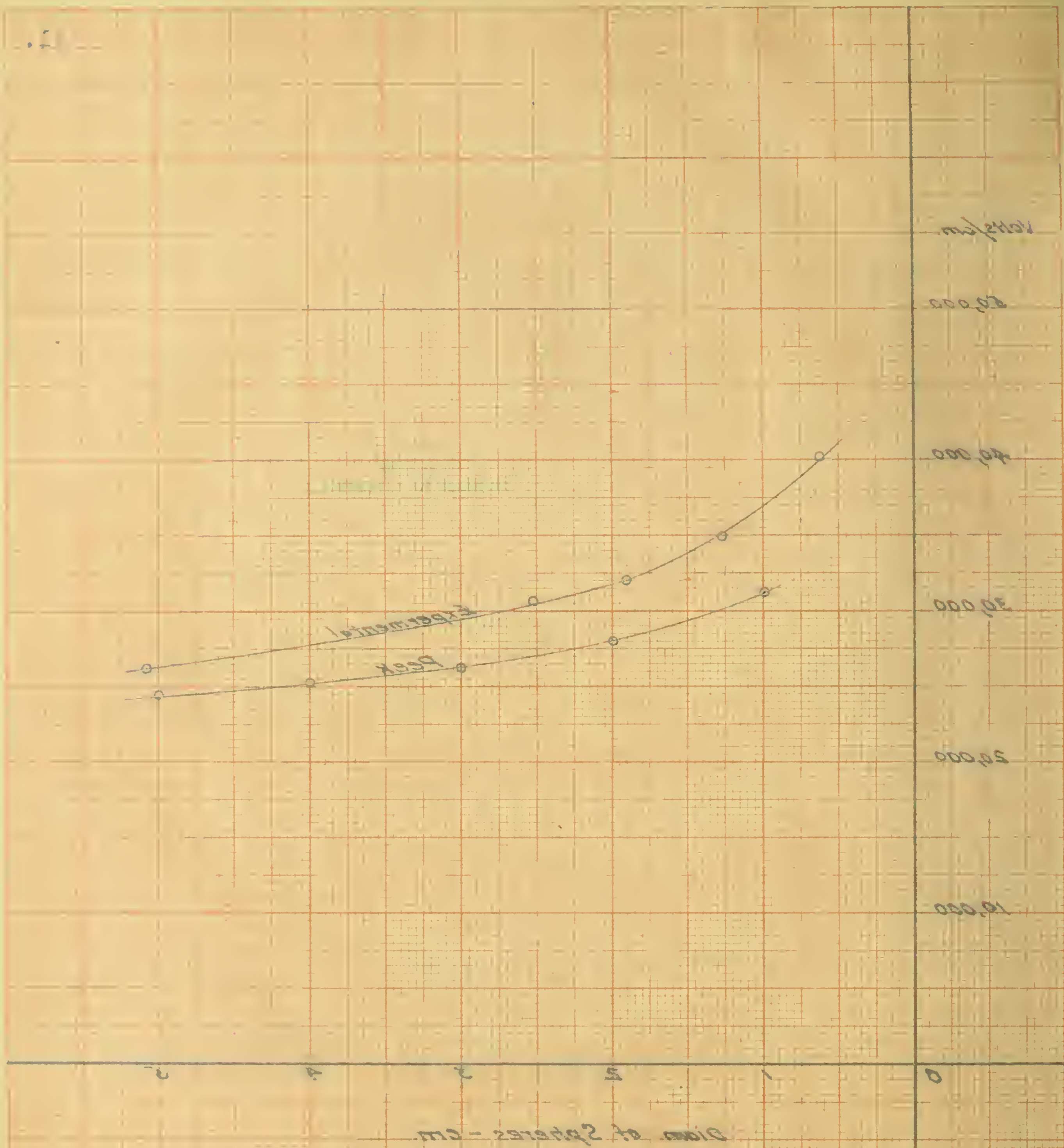


PLATE XII
COMPARISON OF
POTENTIAL GRADIENTS
L.M. Hager — May 15, 1915.

Article 8.

The Effect Of Foreign Materials In Air Gap.

To study the effect of materials of various specific inductive capacity upon the corona and striking voltage, a grounded brass plate was suspended between the terminals. The curve for this is compared to that of the plain gap in Plate 13, using one inch balls in both cases.

The striking voltage with the brass plate in gap is a trifle higher than that of the plain air gap up to the critical point at which point it jumps from 77,500 to 113,500 volts and then follows the curve shown. The corona line is higher than in the case of simple air gap and nearly parallel to it.

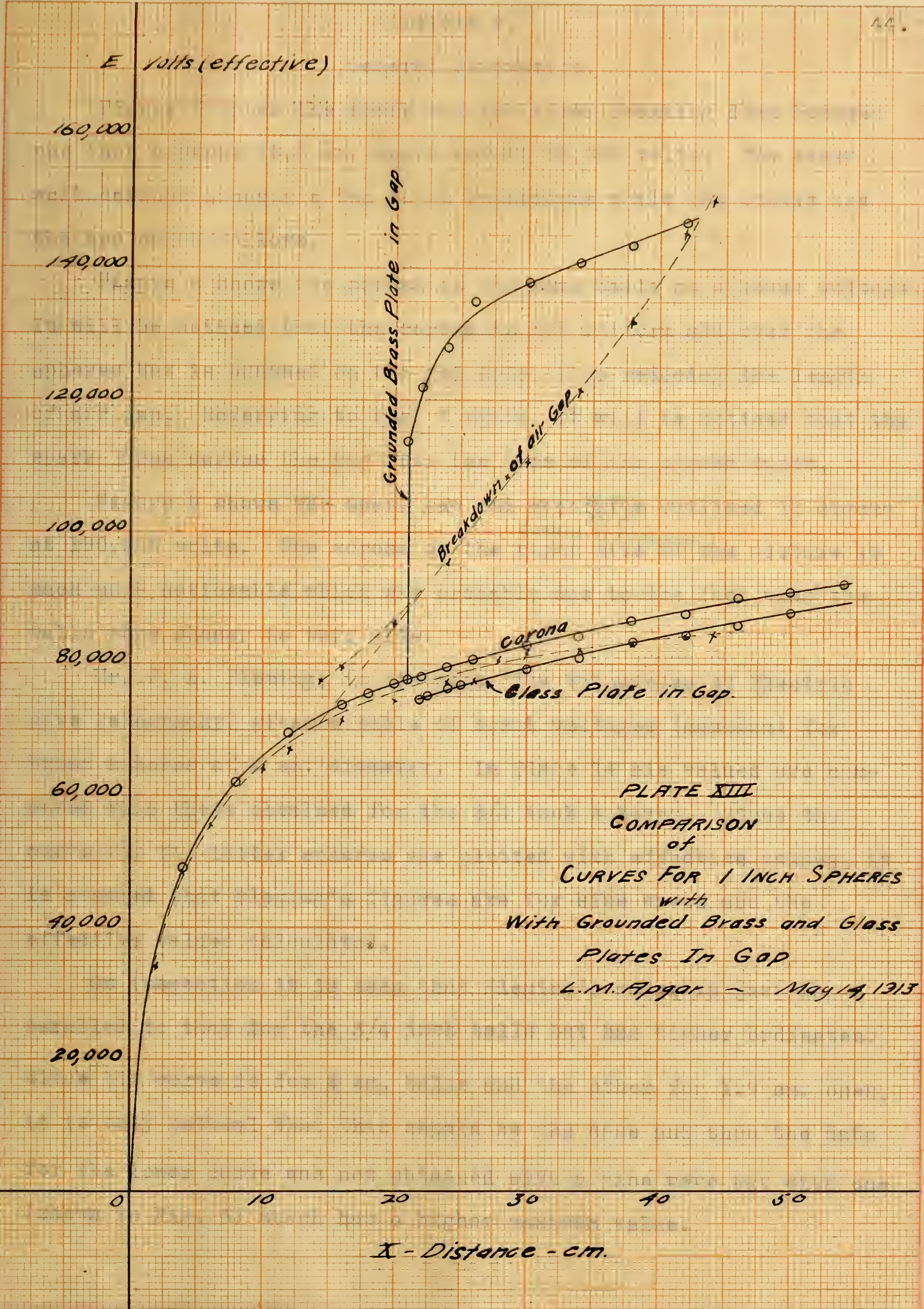
When a glass plate is substituted for the brass one, the corona line is lower but parallel to the one for plain air.

Use of these principles might be made in insulating high tension lines since the striking voltage is materially increased by the grounded brass plate.

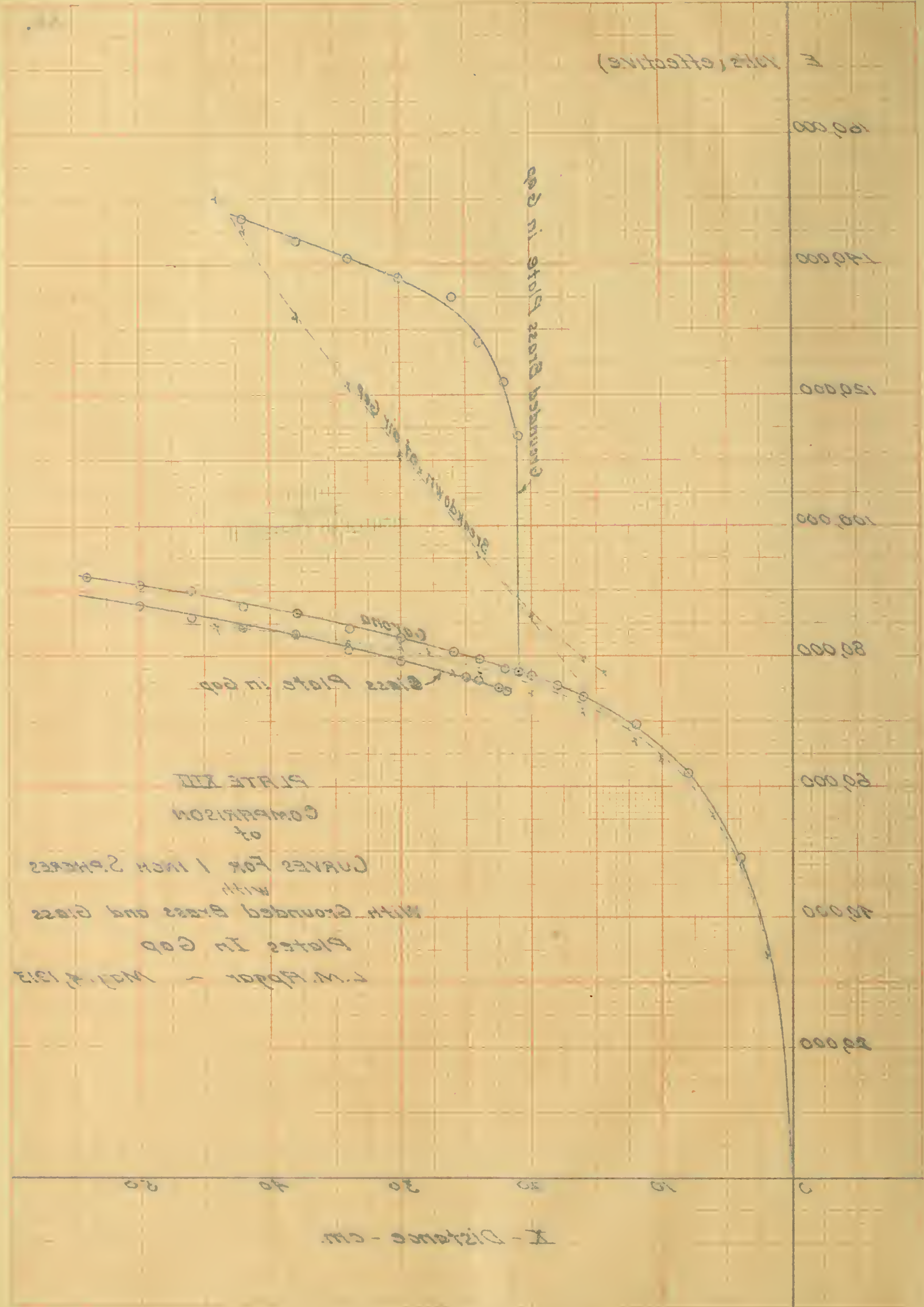
TABLE #11.

FOR 1 INCH SPHERES.

X cm.	Grounded Brass Plate in Gap. Corona Appears. KV.	Grounded Brass Plate in Gap. Break-down. KV.	Glass Plate in Gap. Corona Appears. KV.
4		49.0	
8		62.0	
12		69.5	
16		73.8	
20		77.0	
21	77.5	113.5	
22	78.0	122.0	74.5
24	79.5	128.0	76.0
26	80.5	135.0	76.9
30	82.5	138.0	79.0
34	84.0	141.0	81.0
38	86.5	143.5	83.0
42	87.5	147.0	84.5
46	90.0		86.5
50	91.0		88.0
54	92.0		



E volts (effective)
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
10
20
30
40
50
X - Distance - cm.
Grounded Brass Plate in Gap
Breakdown of air Gap
Corona
Glass Plate in Gap.
PLATE XIII
COMPARISON
of
CURVES FOR 1 INCH SPHERES
with
With Grounded Brass and Glass
Plates In Gap
L.M. Apgar ~ May 14, 1313



E Volts (effective)
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
Grounded Brass Plate in Gap
Breakdown at air Gap
Corona
Glass Plate in Gap
PLATE XIII
COMPARISON
of
CURVES FOR 1 INCH SPHERES
with
With Grounded Brass and Glass
Plates In Gap
L. M. Apgar — May 4, 1913
0
10
20
30
40
50
X - Distance - cm.

Article 9.

General Discussion.

Figure 7 shows the spark and arc after breaking down between one inch spheres 18,5 cm. apart and at 83,000 volts. The sharp, well defined lines are the first breakdowns while the others are the arc which follows.

Figure 8 shows the corona on the same balls at a lower voltage. It will be noticed that the corona is not uniform all over the spheres but is bunched on the gap side, thus reducing the length of air gap. Referring to Fig. 7 again, it will be noticed that the spark jumps across the gap from the tips of the corona tufts.

Figure 9 shows the spark gap and apparatus outlined in corona at 190,000 volts. The corona on the right side of the picture is much more noticeable which was probably due to the fact that the walls were closer to this side.

Mr. J. A. Fleming, in his book "The Principles of Electric Wave Telegraphy", gives a table of spark voltages (maximum) for brass spheres of 2 cm. diameter. In Plate 14 his values are compared with those obtained for the 3/4 inch spheres. Since the curve for the latter spheres are plotted with effective values, it is assumed that Fleming's figures are for sine waves and the effective values calculated.

On inspection it is seen that Fleming's curve is just about paralled to that for the 3/4 inch balls but has higher ordinates. Since his curve is for 2 cm. balls and the other for 1.9 cm. ones, it is only natural that this should be the case and then the data for the lower curve was not obtained with a sine wave but with one (shown in Fig. 6) which has a higher maximum value.

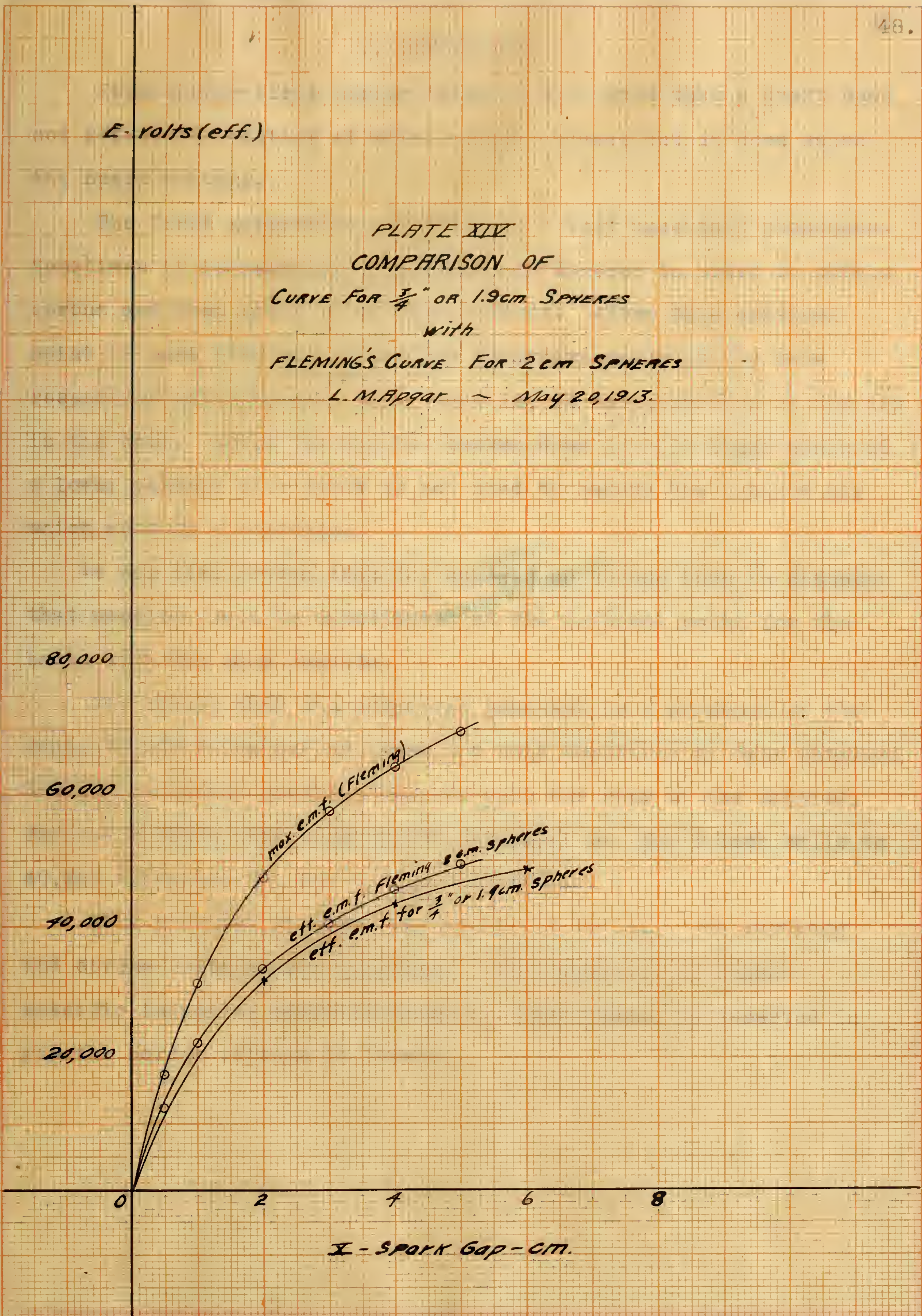
All the curves given by Fleming are of the same general shape as those given in the Plates but are only run for a few millimeters of spark gap; so that they are of no value for comparison at high voltages.

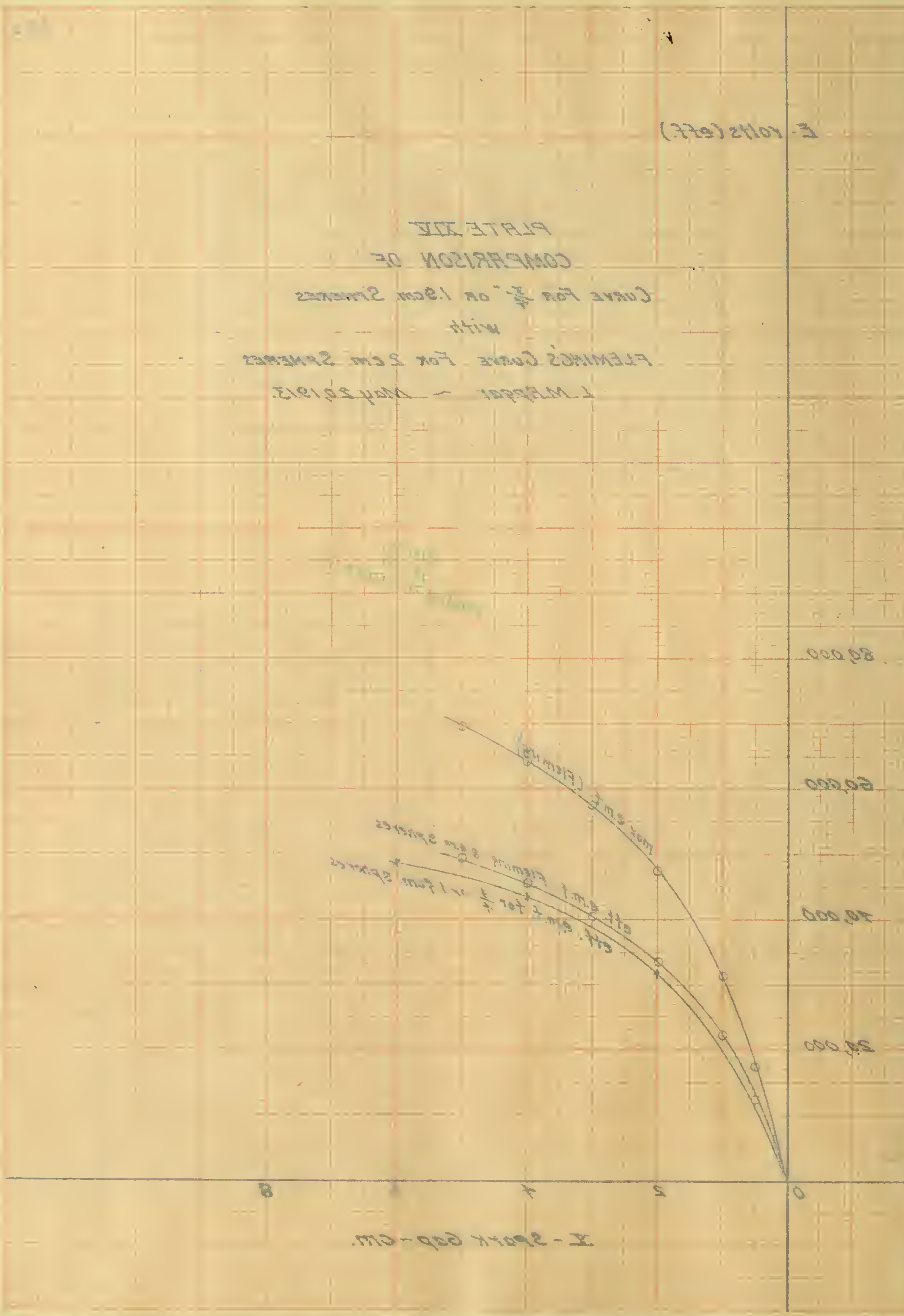
Peek in his paper "The Law Of Corona", gives the curves showing corona and breakdown for parallel conductors, which are of the same general shape as those for spheres except that he does not get the reverse curve in his spark line which was probably due to the fact that he did not carry his voltage high enough.

FIG. 7

FIG. 8

FIG. 9


E · volts (eff.)
PLATE XIV
COMPARISON OF
CURVE FOR 3/4" OR 1.9cm. SPHERES
with
FLEMING'S CURVE FOR 2 cm SPHERES
L. M. Apgar ~ May 20, 1913.
80,000
60,000
40,000
20,000
max. e.m.f. (Fleming)
eff. e.m.f. Fleming 2 c.m. spheres
eff. e.m.f. for 3/4" or 1.9cm. spheres
0
2
4
6
8
X - Spark Gap - cm.


E - volts (eff.)
PLATE XII
COMPARISON OF
Curve for 3/4" on 1.5cm Spheres
with
FLEMING'S Curve for 2 cm Spheres
May 29 1913
80,000
60,000
40,000
20,000
max e.m.f (Fleming)
Fleming 2 cm Spheres
eff. e.m.f
eff. e.m.f for 3/4" on 1.5cm Spheres
0
2
4
8
X - Spark Gap - cm.

V. CONCLUSION.

From observations during tests it was noted that a draft does not affect the voltage at which corona appears but it does raise the spark voltage.

The first appearance of corona is a very uncertain phenomena. Sometimes it is necessary to polish the spheres in order to obtain corona and then again it appears without. After this critical point is past both the corona and breakdown occur at the same respective voltages each time, that is, if the condition of the air is the same. After the air has broken down it will break again at a lower voltage if a draft is not used to remove the ionized air which acts as a conductor.

It was also proven that for spheres up to one inch in diameter that needles could be substituted at the critical point for the balls with the same results.

The theory that the potential gradient is a constant of the value 30,000 volts per cm. does not hold according to data obtained but the potential gradient depends upon the size of the spheres, varying in this case from 26,100 volts per cm. for 2 inch balls to 40,200 volts per cm. for 1/4 inch spheres.

If a grounded conductor is placed in the gap, the striking and corona voltages are increased. If a material of higher specific inductive capacity than air, like glass, is inserted in gap the corona voltage is lowered.

VI. REFERENCES.

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